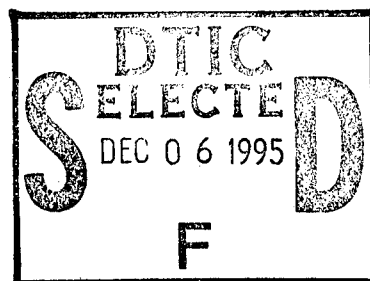


AFIT/GAE/ENY/95D-05



COMPARISON OF THE RALPH SMITH
AND THE TIME DOMAIN FLYING QUALITIES
CRITERIA

THESIS

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AFIT/GAE/ENY/95D-05

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COMPARISON OF THE RALPH SMITH AND THE TIME DOMAIN FLYING QUALITIES CRITERIA

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
In Partial Fulfillment of the
Requirements for the Degree of
Master of Science in Aeronautical Engineering

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December, 1995

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Lori Ann Carlucci

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List of Symbols

<u>Symbol</u>	<u>Description</u>
\bar{c}	Mean Aerodynamic Chord
CAP	Control Anticipation Parameter
C_{D1}	Coefficient of Drag at Equilibrium
$C_{L\alpha}$	Coefficient of Lift due to Angle of Attack
$C_{L\delta_e}$	Coefficient of Lift due to Elevator Deflection
$C_{m\alpha}$	Coefficient of Pitching Moment due to Angle of Attack
$C_{m\delta_e}$	Coefficient of Pitching Moment due to Elevator Deflection
F_s	Stick Force
h	Altitude
I_{yy}	Moment of Inertia about Pitch Axis
K_c	Forcing Function Gain
K_θ	Pitch Transfer Function Gain
LOC	Loss of Control

<u>Symbol</u>	<u>Description</u>
m	Mass of Aircraft
M_{α}	Dimensional Variation of Pitching Moment with Angle of Attack
$M_{\dot{\alpha}}$	Dimensional Variation of Pitching Moment with Rate of Change of angle of Attack
M_{δ_e}	Dimensional Variation of Pitching Moment with Elevator Deflection
n/α	Ratio of Load Factor to Angle of Attack
$N_{\delta_e}^{\theta}$	Numerator of Transfer Function $\frac{\theta}{\delta_e}$
\bar{q}_1	Dynamic Pressure
q_{ss}	Steady State Pitch Rate
s	Laplace Variable
S	Wing Reference Area
\bar{S}	Average Slope on $1 \leq \omega \leq 6$
SAS	Stability Augmentation System

<u>Symbol</u>	<u>Description</u>
t_1	Equivalent Time Delay
t_2	Time Measured from Input to Intersection of Maximum-Slope Line with Steady State Line
t_q	Time To First Peak
T_{θ_1}	Low Frequency Pitch Attitude Zero
T_{θ_2}	High Frequency Pitch Attitude Zero
TPR	Transient Peak Ratio
U_1	Steady State Velocity
V_T	True Velocity
Z_α	Dimensional Variation of the Force in the Z Direction with Change in Angle of Attack
Z_{δ_e}	Dimensional Variation of the Force in the Z Direction with Elevator Deflection
δ_e	Elevator Deflection
Δq_1	Maximum Pitch Rate Minus Steady State Pitch Rate
Δq_2	Steady State Pitch Rate Minus First Minimum Pitch Rate

<u>Symbol</u>	<u>Description</u>
$\Delta q_2/\Delta q_1$	Transient Peak Ratio
Δt	Rise Time Parameter
ζ_p	Damping Ratio of the Phugoid Mode
ζ_{sp}	Damping Ratio of the Short Period Mode
θ	Pitch Angle
τ_θ	Aircraft Time Delay
ω_c	Criterion Frequency
ω	Frequency
ω_{sp}	Undamped Natural Frequency of the Short Period Mode
ω_p	Undamped Natural Frequency of the Phugoid Mode
$\angle \frac{\theta}{F_s}(j\omega_c)$	Phase Lag at Criterion Frequency

Abstract

Aircraft pitch response is a crucial element of piloted vehicle flying qualities. The short term pitch response has created controversy over the form and substance of any requirements. Currently there are six different methods for evaluation in MIL-STD-1797A. There are many other methods which have been proposed. The biggest problem is that many of these methods often give conflicting results. The overall goal of the present effort is to compare and contrast the Time Domain criterion and the Ralph Smith criterion. By examining these methods on common grounds, areas of agreement and discrepancies can be found. Parametric studies are performed and trends identified.

COMPARISON OF THE RALPH SMITH AND THE TIME DOMAIN FLYING QUALITIES CRITERIA

I. Introduction

There are many elements in aircraft flight mechanics which contribute to the overall flying qualities of an aircraft. These include the pitch response, roll response, and yaw response. One of the most important is the short-term pitch response of an aircraft. MIL-STD-1797A, *Flying Qualities of Piloted Aircraft* [1], offers six different methods for evaluating short-term pitch response. Each method has strengths and weaknesses depending on aircraft classification and flight phase. All six methods have been maintained because the short-term pitch response characteristics are regarded as important[1]. MIL-STD-1797A provides some guidance for determining the appropriate method to apply. Still, one must decide upon which of the six methods to include in a specification. The simple answer of including all six will lead to conflicting results [1]. There are also recognized methods that are not in MIL-STD-1797A, but are used by people in the industry, such as Numerator Time Constant, Bandwidth and Phase Sensitivity, and the Ralph Smith criterion [2] that create similar types of conflict.

Two methods are analyzed in this research – the Time Domain criterion, from MIL-STD-1797A [1], and the Ralph Smith criterion, from AFFDL-TR-78-154 [3]. By comparing these criteria, it can be seen where regions of conflict and agreement are located. This will aid in making a decision to either keep the criteria the way they are, modify them, or possibly even combine them into one new criterion.

1.1 Overview

The study of flying qualities is the discipline in aeronautical engineering that is concerned with basic aircraft stability and controllability. 'Flying qualities,' 'stability and control,' and 'handling qualities' are three terms which are generally considered synonymous [4]. To

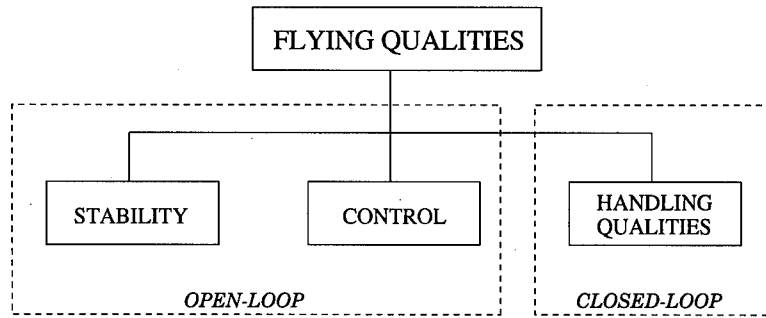


Figure 1.1: Flying Qualities Breakdown

prevent confusion, the following definitions will be used. Both the US Air Force Test Pilot School and US Naval Test Pilot School agree that “*flying qualities* are those stability and control characteristics which influence the ease of safely flying an aircraft during steady and maneuvering flight in the execution of the total mission” [5]. Edkin defines *stability* as “...the tendency or lack of it, of an airplane to fly with wings level” and *control* as “...steering an airplane on an arbitrary flight path” [6]. Cooper and Harper define *handling qualities* as “...those qualities or characteristics of an aircraft that govern the ease and precision with which a pilot is able to perform the tasks required in support of an aircraft role” [7]. Fig.(1.1) shows how flying qualities, stability, control, and handling qualities are related to one another. The figure shows that stability, control and handling qualities are all subgroups of flying qualities.

Stability and control analysis deals with the interaction of the control surfaces with the external forces and moments on the aircraft [8]. Generally, stability and control analysis primarily deals with systems that are still in the design phase, as shown in Fig.(1.2). Note that there is no pilot in this system. A stick force, F_s , is applied, which goes through the control system, to produce an elevator deflection, δ_e . This elevator deflection is fed into the aircraft dynamics to produce the desired pitch response.

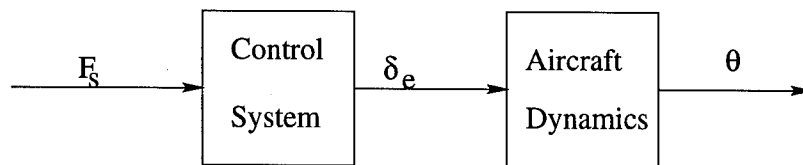


Figure 1.2: Open Loop System

On the other hand, handling qualities assessment deals with the pilot and aircraft performing as a closed-loop system, as shown in Fig.(1.3). The pilot wants a desired pitch angle, θ , so he puts in a stick force. The input goes through the control system and aircraft dynamics. The resulting pitch angle is feed to the stability augmentation system, SAS, and back to the pilot, where he determines if more input is needed. The main difference, then, is that stability and control require analysis without a pilot, while handling qualities is considered an analysis with a pilot in the loop. In this research, the term open-loop is used to signify that there is no pilot in the analysis of the aircraft transfer function, while closed-loop means a pilot model is in the analysis.

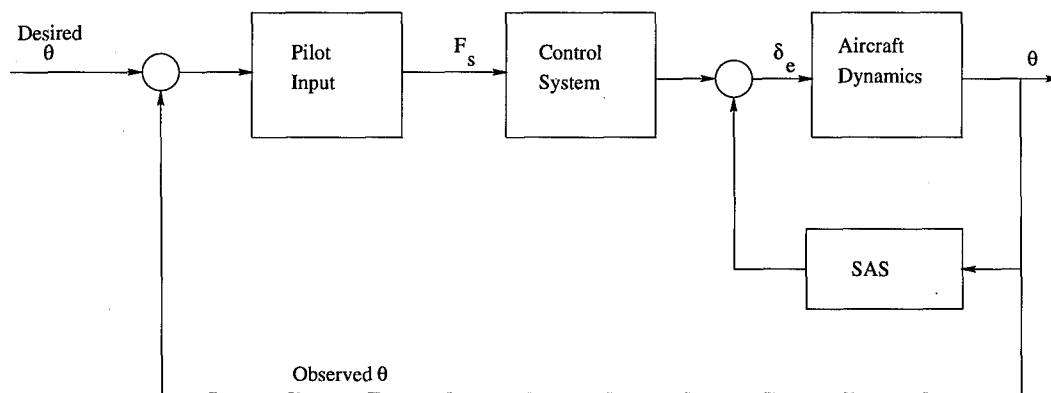


Figure 1.3: Closed Loop System

The six methods offered by MIL-STD-1797A are used to *predict* handling qualities while the aircraft is still in the development phase. Since aircraft perform a wide variety of maneuvers and vary in size, some type of grouping is necessary before analysis can begin. The class designations, as described in MIL-STD-1797A, are used to help determine the requirements according to broad categories of intended use. The intended use of an aircraft must be known before required configurations, loadings and operational flight envelopes can be defined. Four classes of aircraft are defined by MIL-STD-1797A and are outlined in Table 1.1.

This research examines a range of T_{θ_2} values representative of two different aircraft. The first is Calspan Corporation's variable stability Learjet 24 shown in Fig.(1.4). The second is the Variable Stability In-flight Simulator (VISTA) which uses the F-16D as its host aircraft, pictured in Fig.(1.5). The Learjet can be considered a Class II aircraft, while the F-16

Table 1.1: Aircraft Classification

<i>Class</i>	<i>Description</i>	<i>Example</i>
I	small light aircraft	T-41, OV-10
II	medium weight aircraft with low-to-medium maneuverability	C-21, C-130
III	large, heavy aircraft with low-to-medium maneuverability	KC-10, B-2
IV	highly maneuverable aircraft	F-16, F-117

VISTA can be considered a Class IV aircraft. Using variable stability aircraft makes it possible to flight test the analytic results of this present study in future research. The cockpit environment can be changed to match that of another aircraft. Since an aircraft is being flown, it provides a degree of realism that cannot be duplicated in a ground-based simulation. As the pilot moves the controls, he can experience the true flight motions, accelerations, and handling qualities of the simulated aircraft [9]. This realism gives the pilot a higher level of confidence when determining a handling qualities level.

In this research, a mapping will be provided to show regions of agreement and conflict for two of the different methods used to predict handling qualities. Since every point in the region represents a different aircraft transfer function, a variable stability aircraft, such as the VISTA F-16, can be configured to represent one of these transfer functions. A point in a region of conflict could be programmed into the flight control system so a test pilot could fly the simulated aircraft and determine the real handling qualities level. If enough cases are flight tested and the results show a specific trend, a decision could be made on whether one of the methods used to predict handling qualities needs to be modified or even eliminated.

Experience with aircraft operations indicate that certain flight phases require more stringent values of flying qualities parameters [1]. MIL-STD-1797A defines three categories of flight phases, outlined in Table 1.2. This research only examines the Category C flight phase, approach and landing. However, the method derived in Chapter III of this present effort can handle any flight phase category. With aircraft classification and flight phase known, handling qualities levels can be addressed.

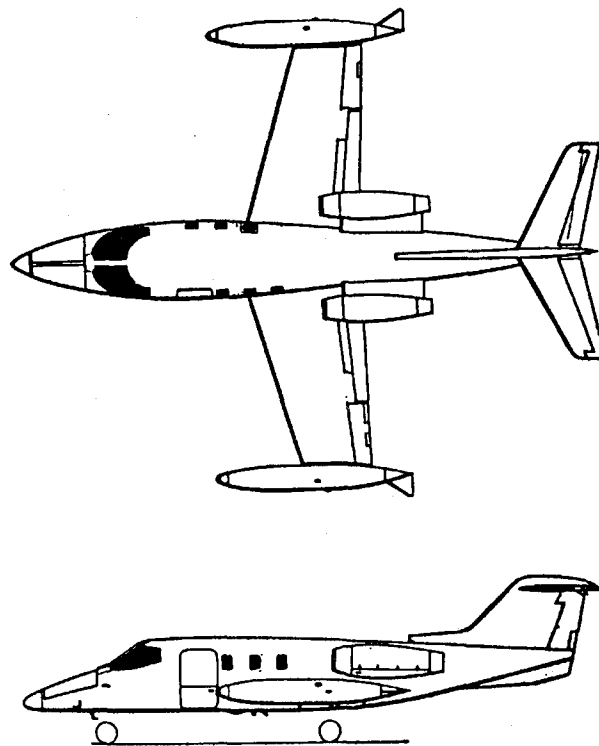


Figure 1.4: Lear Jet

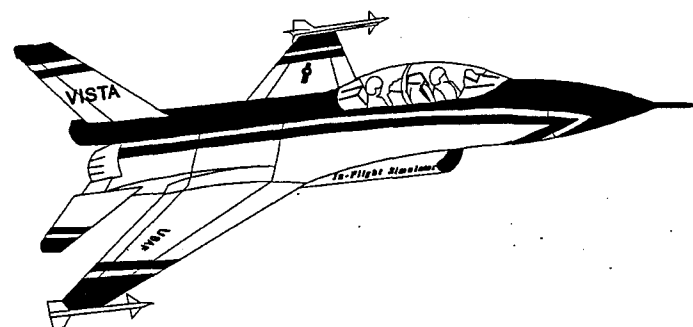


Figure 1.5: F-16 VISTA

Table 1.2: Flight Phase Categories

<i>Category</i>	<i>Description</i>	<i>Example</i>
A	nonterminal flight phases that require rapid maneuvering, precision tracking, or precise flight-path control	air-to-air combat
B	nonterminal flight phases that require gradual maneuvering without precision tracking	climb
C	terminal flight phases that require gradual maneuvering with accurate flight-path control	landing

When determining the handling qualities of an aircraft, a pilot must answer a series of questions. These questions lead to a pilot opinion rating on the Cooper-Harper scale [7]. The scale was developed over the years as a means of putting a short-hand symbol to the comments the pilots made about a aircraft performance [7]. By answering a series of yes-no questions, the pilot can relate the controllability, the workload requirements and the amount of improvement needed.

MIL-STD-1797A defines three levels of handling qualities, outlined in Table 1.3 [1]. These levels are based on the the Cooper-Harper scale, shown in Fig.(1.6) [1]. A correlation between the Cooper-Harper scale and the handling qualities levels defined by MIL-STD-1797A. A Cooper-Harper rating of 1 to 3 defines the Level 1, 4 to 6 defines Level 2, and 7 through 9 are Level 3 [7].

1.2 Previous Work

Work done on the topic of handling qualities comparison is not limited to this research. Research is done on a continuing basis at the Flight Dynamics Directorate of Wright Laboratory. The Handling Qualities group is currently working on comparison mappings for the different flight phases. This work is on going in an attempt to determine which criteria to include in a revision of MIL-STD-1797A.

Another source of work done was performed by Kish [10] for his Master's Thesis at the Air Force Institute of Technology. His research examined the Neal-Smith criterion and

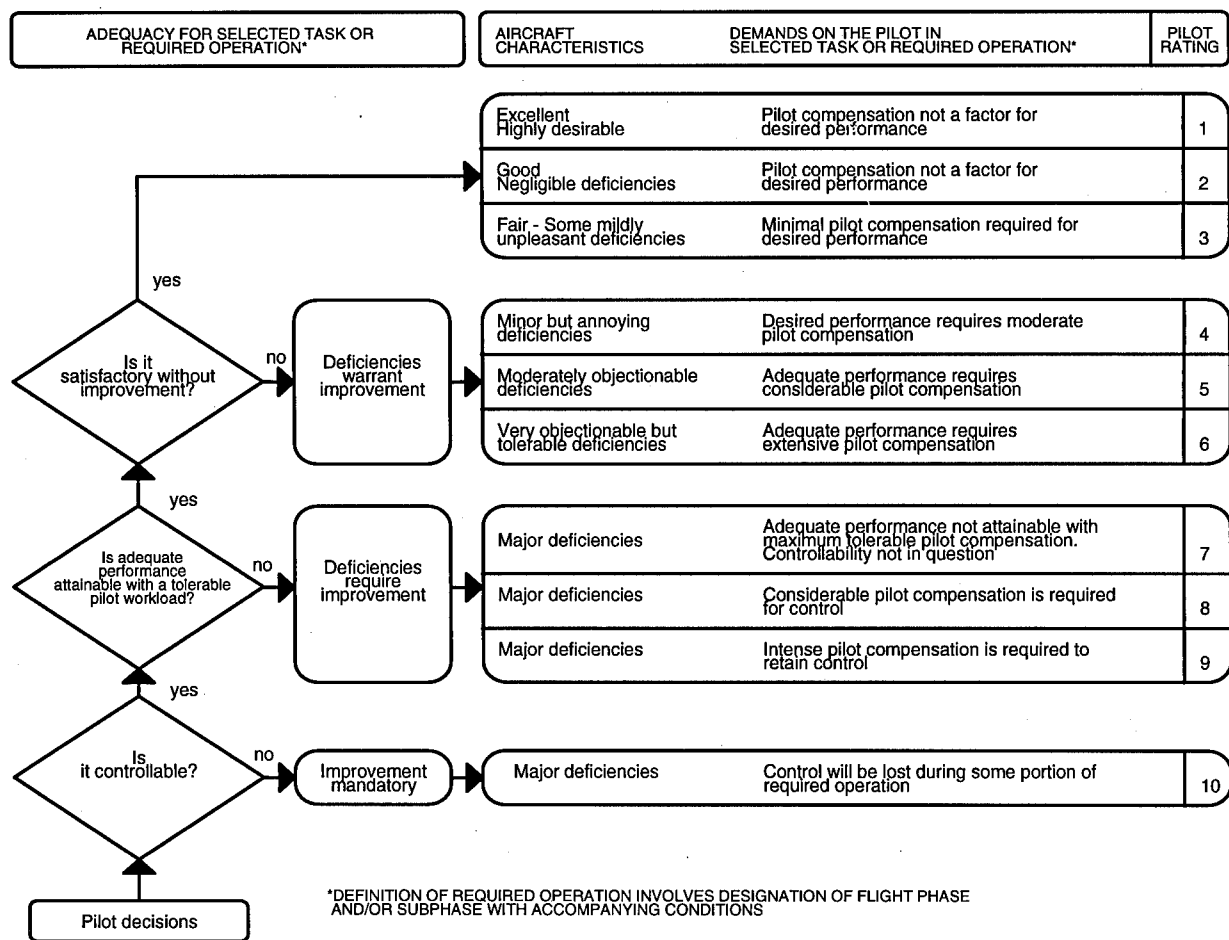


Figure 1.6: Cooper-Harper Scale

Table 1.3: Handling Qualities Levels

<i>Level</i>	<i>Meaning</i>	<i>Description</i>
1	satisfactory	Flying qualities clearly adequate for the mission flight phase. Desired performance is achievable with no more than minimal pilot compensation.
2	acceptable	Flying qualities adequate to accomplish the mission flight phase, but some increase in pilot workload and/or degradation in mission effectiveness exists.
3	controllable	Flying qualities are such that the aircraft can be controlled in the context of the mission flight phase, even though pilot workload is excessive and/or mission effectiveness is inadequate.

the $\omega_{sp}, \zeta_{sp}, T_{\theta_2}, \tau_{\theta}$ criterion. The Neal-Smith criterion, as well as the less restrictive Pilot-in-the-Loop criterion, uses an optimal pilot model to predict the handling qualities of an aircraft. Kish compares both of these closed loop methods with the open loop $\omega_{sp}, \zeta_{sp}, T_{\theta_2}, \tau_{\theta}$ criterion, in order to compare the results, in the landing phase of flight.

Work on yet another topic, similar in nature, is also being flight tested at the US Air Force Test Pilot School, by Kivioja [11]. In that research, the control anticipation parameter, CAP, is compared to the Bandwidth the landing phase. In the test phase of the research, pilots will evaluate the landing task using the Cooper-Harper rating scale [11]. These results will then be compared to the predicted ratings received by evaluation of the criteria.

1.3 Research Objectives

The overall goal of the present effort is to compare and contrast the Time Domain criterion and the Ralph Smith criterion. In order to accomplish this overall goal, some specific objectives must be met.

1. Develop a computer code enabling the two criteria to be examined at each transfer function in a grid of the undamped natural frequency, ω_{sp} versus the damping ratio, ζ_{sp} .
2. Develop a mapping system to identify the areas of conflict and agreement between the criteria.
3. Perform a parametric study to identify trends for areas of agreement.

1.4 General Approach

An aircraft transfer function can be described by five parameters: ω_{sp} , T_{θ_2} , ζ_{sp} , K_{θ} and τ_{θ} . By holding T_{θ_2} , K_{θ} and τ_{θ} constant while varying ω_{sp} and ζ_{sp} a two dimensional region of aircraft transfer functions can be created. Once each transfer function is determined, the handling qualities level according to the Ralph Smith criteria is then determined. This creates a map in a grid of ω_{sp} vs. ζ_{sp} of the Ralph Smith criteria. The same procedure is done for the Time Domain criteria. The two criteria are then compared to determine the areas of conflict and agreement.

1.5 Overview

This research is separated into four chapters. Chapter II contains the background information necessary for understanding the short-period pitch response of an aircraft. Also included is the background material of the criteria involved in the mappings. Chapter III describes the results of completing Objective 1 and Objective 2. A sample mapping is provided to illustrate the algorithm. The results of the parametric study, Objective 3, is presented in Chapter IV. Chapter V gives the conclusions which were drawn from this research.

II. Pitch Response Criteria

This chapter describes the aircraft pitch response in general and the pitch response criteria examined in this research. First, the background material on the short period approximation is given. Next, the description and pertinent information on the Ralph Smith and the Time Domain criteria is given. Finally, an example of how to apply the two criteria to an aircraft transfer function is presented.

2.1 Background

In aircraft control theory, it is not uncommon to have feedback control systems of twentieth order or more. Writing a specification for such a large system can be cumbersome. Considerable research has been devoted to reducing the order of these high-order feedback control systems by matching frequency responses to obtain lower-order equivalent systems. Using lower-order equivalent systems allows the application of well-established boundaries generated by classical airplane data to be extended to many high order systems [1]. The pitch angle transfer function, $\frac{\theta}{\delta_e}$, for a linearized, reduced-order model of the aircraft is given as

$$\frac{\theta(s)}{\delta_e(s)} = \frac{K_\theta (T_{\theta_1} \cdot s + 1) (T_{\theta_2} \cdot s + 1) e^{-\tau_\theta \cdot s}}{(s^2 + 2\zeta_p \omega_p \cdot s + \omega_p^2) (s^2 + 2\zeta_{sp} \omega_{sp} \cdot s + \omega_{sp}^2)} \quad (2.1)$$

where

θ	--	Pitch Angle
δ_e	--	Elevator Deflection
K_θ	--	Pitch Transfer Function Gain
T_{θ_1}	--	Low Frequency Pitch Attitude
T_{θ_2}	--	High Frequency Pitch Attitude Zero
τ_θ	--	Aircraft Time Delay
ζ_p	--	Damping Ratio of the Phugoid Mode
ω_p	--	Undamped Natural Frequency of the Phugoid Mode
ζ_{sp}	--	Damping Ratio of the Short Period Mode
ω_{sp}	--	Undamped Natural Frequency of the Short Period Mode
s	--	Laplace Variable

K_θ can be further defined in terms of the non-dimensional stability derivatives as

$$K_\theta = \frac{\bar{q}_1^2 S^2 \bar{c} [C_{m_{\delta_e}} (C_{L_\alpha} + C_{D_1}) - C_{m_\alpha} C_{L_{\delta_e}}]}{I_{yy} m U_1} \quad (2.2)$$

where

\bar{q}_1	---	Dynamic Pressure
S	---	Wing Reference Area
\bar{c}	---	Mean Aerodynamic Cord
C_{m_α}	---	Coefficient of Moment due to Angle of Attack
$C_{L_{\delta_e}}$	---	Coefficient of Lift due to Elevator Deflection
$C_{m_{\delta_e}}$	---	Coefficient of Moment due to Elevator Deflection
C_{L_α}	---	Coefficient of Lift due to Angle of Attack
C_{D_1}	---	Coefficient of Drag at Equilibrium
I_{yy}	---	Moment of Inertia
m	---	Mass of Aircraft
U_1	---	Equilibrium Velocity

The detailed derivation of Eq.(2.2) is shown in Appendix A.

In cases where the forward velocity response is small at the natural frequency of the short-period, further reduction is possible [12]. The low frequency, low damping pole, or phugoid mode, can be separated from the high frequency, high damping short period mode. This is done by setting the forward speed, u , to zero in the equations of motion and neglecting the forces in the X direction, since they contribute mostly to the changes in forward speed. In such cases,

$$\frac{\theta(s)}{\delta_e(s)} = \frac{K_\theta(T_{\theta_2} \cdot s + 1)e^{-\tau_\theta \cdot s}}{s(s^2 + 2\zeta_{sp}\omega_{sp} \cdot s + \omega_{sp}^2)} \quad (2.3)$$

may be used in place of Eq.(2.1) and is called the short-period approximation.

For example, the following pitch transfer function,

$$\frac{\theta(s)}{\delta_e(s)} = \frac{-1.31(s + 0.016)(s + 0.3)e^{-.1s}}{(s^2 + 0.00466s + 0.0053)(s^2 + 0.806s + 1.311)} \quad (2.4)$$

is for an four engine jet transport flying straight and level at Mach number 0.62 [12]. The short-period approximation for Eq.(2.4) is

$$\frac{\theta(s)}{\delta_e(s)} = \frac{-1.39(s + 0.306)e^{-.1s}}{s(s^2 + 0.805s + 1.325)} \quad (2.5)$$

Fig.(2.1) compares Bode plots of the original higher order system to the short-period approximation. For this example, the short-period approximation describes the aircraft pitch response fairly well for the frequency range given.

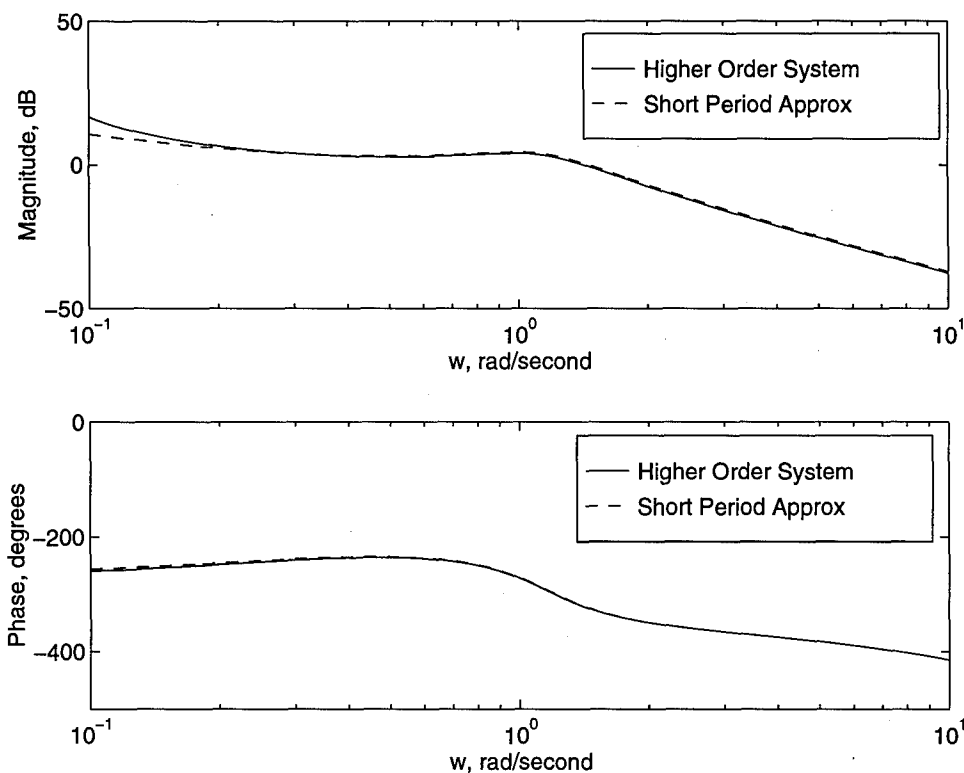


Figure 2.1: Bode Magnitude and Phase Plots for the Jet Transport

2.2 Ralph Smith Handling Qualities Criterion

The Ralph Smith criterion combines time response methods of determining handling qualities with frequency response methods [3]. Time response methods are those that use the response to an input to relate handling qualities with aircraft parameters such as rise time, or settling time. Frequency response criteria, on the other hand, predict the handling qualities by relating parameters to a pilot model. The Ralph Smith criterion is an open-loop criterion, as shown in Fig.(1.2), but was derived using an optimal pilot model as well as flight test data from Neal and Smith [13].

The Ralph Smith criterion, as well as the Time Domain criterion, is three-dimensional, as seen in Table 2.1. The criterion consists of three parameters, time to first peak, t_q , average slope, \bar{S} , and phase lag, $\angle \frac{\theta}{F_s}(j\omega_c)$. In order to determine the handling qualities level, one must go through all three parameters. The overall value is determined by the worst rating of the three parameters. For example, if the three ratings are 1,2, and 3, then the overall handling qualities level would be Level 3.

Table 2.1: Ralph Smith Criterion

<i>Parameter</i>	<i>Level 1</i>	<i>Level 2</i>	<i>Level 3</i>
t_q (secs)	$.2 \leq t_q \leq .9$	None	None
\bar{S} (dB/oct)	≤ -2	None	None
$\angle \frac{\theta}{F_s}(j\omega_c)$	$\leq -123^\circ$	$\leq -165^\circ$	$\leq -180^\circ$

When a pilot is determining the handling qualities of an aircraft, there are many questions that must be answered. Two of the important of these questions are as follows:

Is the response too abrupt or too sluggish?

Does the response require considerable pilot compensation?[3]

The first question can be answered by time history analysis, while the second question can be answered by looking at the frequency response of the aircraft.

2.2.1 Time to First Peak, t_q

The time to first peak parameter, t_q , is defined as the time to first peak of the pitch rate response, $q(t)$, to a step input of stick force. If the response is over-damped, t_q is defined as the time to 90 percent of the steady state value[3]. The lower bound is an approximate representation of the limit on human time delay. If $t_q < .2$ seconds the pilot tends to chase the response. The typical pilot comment would be that the aircraft response is too abrupt. With a time to first peak less than .2 seconds, precision maneuvering will be difficult without excessive pilot compensation [3]. The upper bound is set from the Neal-Smith flight test data. From pilot comments it was noted that a system with $t_q > .9$ tends to be too sluggish. This results from excessive lag in the phase angle of $\frac{\theta}{F_s}(j\omega_c)$ [3]. Fig.(2.5) shows a plot of the average Cooper-Harper rating given to the Neal-Smith flight test data versus t_q . The numerical data is given in Appendix B. By looking at this data, it can be seen that these bounds are adequate, since no Level 1 ratings occur outside the bounds which mark the Level 1 region.

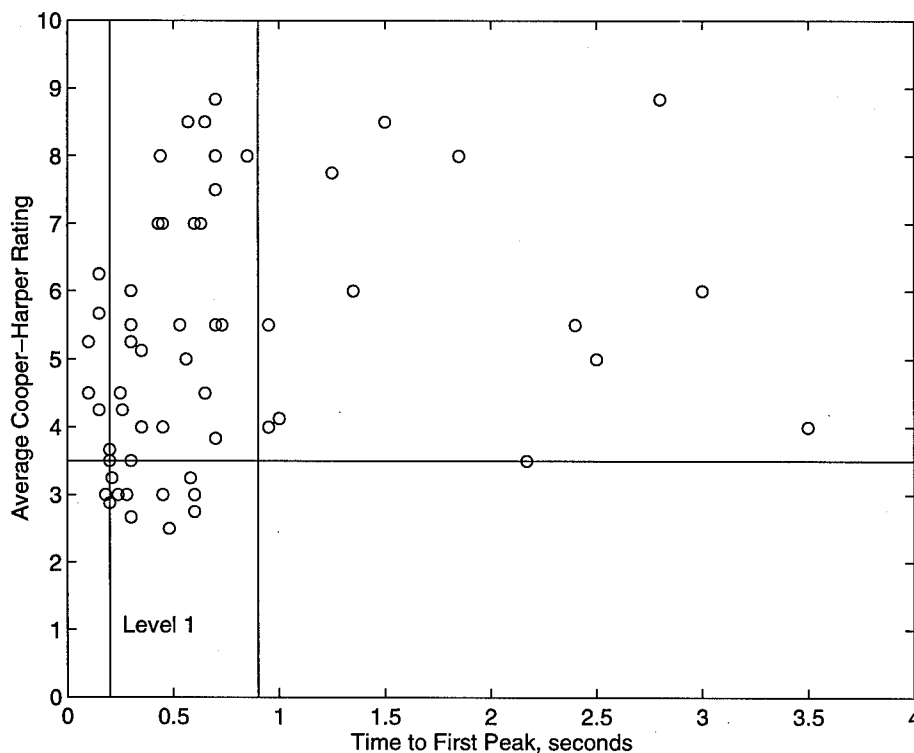


Figure 2.2: Average Cooper-Harper Rating vs. Time to First Peak of Neal-Smith Test Data

2.2.2 Slope Parameter, \bar{S}

The slope parameter, \bar{S} , is defined as the average slope of the magnitude plot of the transfer function $\frac{\theta}{F_s}(j\omega)$ on the frequency range of $1 \leq \omega \leq 6$ radians/second. This slope is representative of the sensitivity of the response to pilot technique [3]. The parameter takes into account the variability of pilots by requiring the slope to be small, thus making the aircraft resistant to different pilot techniques or skill level. The magnitude of the slope can be determined using a least squares best fit straight line on the frequency range.

The boundaries were determined by dividing the Neal-Smith flight test data into three groups,

$$\bar{S} \geq -2dB/oct \quad (2.6)$$

$$-2 > \bar{S} \geq -6dB/oct \quad (2.7)$$

$$\bar{S} < -6dB/oct \quad (2.8)$$

Eq.(2.6) yields degraded handling qualities and is too abrupt, similar to a pure gain forcing function, K_c . Eq.(2.7) produces good results if $\angle \frac{\theta}{F_s}(j\omega_c) > -130^\circ$. If this is true, the aircraft

performance is governed by the forcing function $\frac{K_c}{s}$. This forcing function represents a simple stereotype of the general classification of aircraft-FCS dynamics which was determined in McRuer's experiments in [15]. $\frac{K_c}{s}$ turned out to have the optimum handling qualities of all the forcing functions tested. Eq.(2.8) acts like $\frac{K_c}{s^2}$ which exhibits excessive phase lag and is stable only with pilot compensation [3]. The criterion ignores the region described by Eq.(2.8), because it is usually not possible to get a Level 1 aircraft, and sets the boundaries as $\bar{S} < -2$ dB/octave. The results are shown in Fig.(2.3) using the flight test data. No Level 1 ratings were given to aircraft with $\bar{S} > -2$ dB/octave.

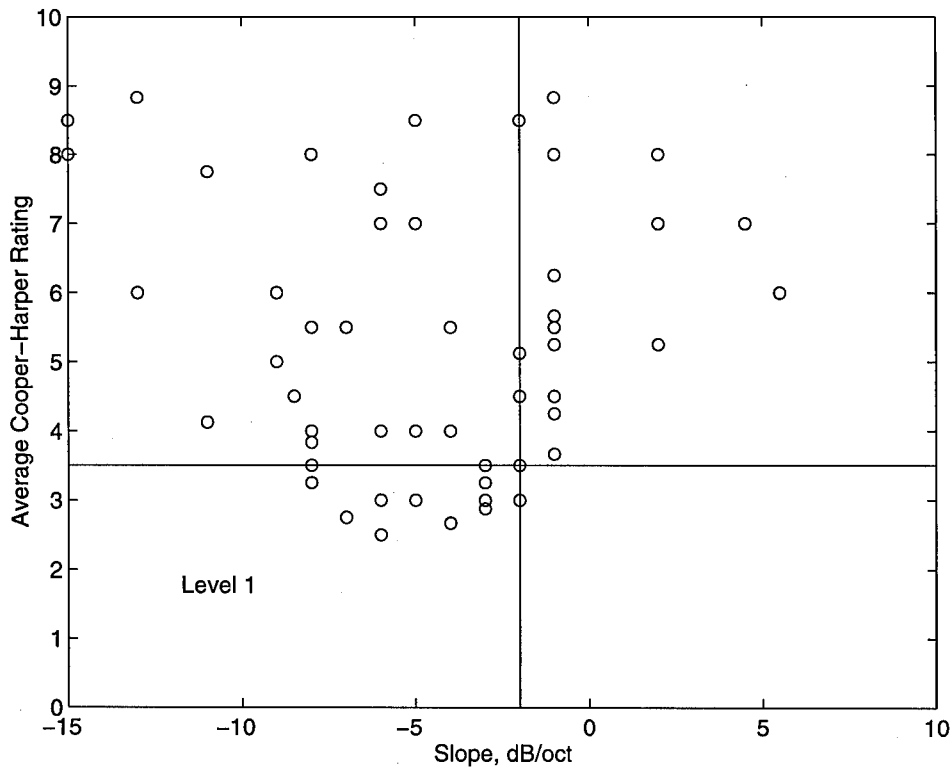


Figure 2.3: Average Cooper-Harper Rating vs. Slope of Neal-Smith Test Data

2.2.3 Phase Lag Parameter, $\angle \frac{\theta}{F_s}(j\omega_c)$

The phase lag quantifies the level of pilot compensation needed to perform maneuvers. The criteria levels were determined from flight test data and pilot comments. Physically, phase lag is the amount of time between the input of a command and when the response of the aircraft is noticed by the pilot. In order to calculate $\angle \frac{\theta}{F_s}(j\omega_c)$, the criterion frequency, ω_c , needs to be determined. This criterion frequency is approximately the crossover frequency of

the pilot-aircraft system for pitch angle tracking. It was determined by using the crossover frequency of the forcing functions, K_c , K_c/s , and K_c/s^2 from McRuer's experiments [15]. By plotting these crossover frequencies against the forcing functions' slopes in dB/octave, the criterion frequency can be defined. Fig.(2.4) shows that the criterion frequency is given by the equation of the best fit straight line through the crossover frequencies.

$$\omega_c = .24\bar{S} + 6.0 \quad (2.9)$$

Once the criterion frequency is calculated, $\angle \frac{\theta}{F_s}(j\omega_c)$ can be found. This is done by locating the phase angle at ω_c on the Bode phase plot.

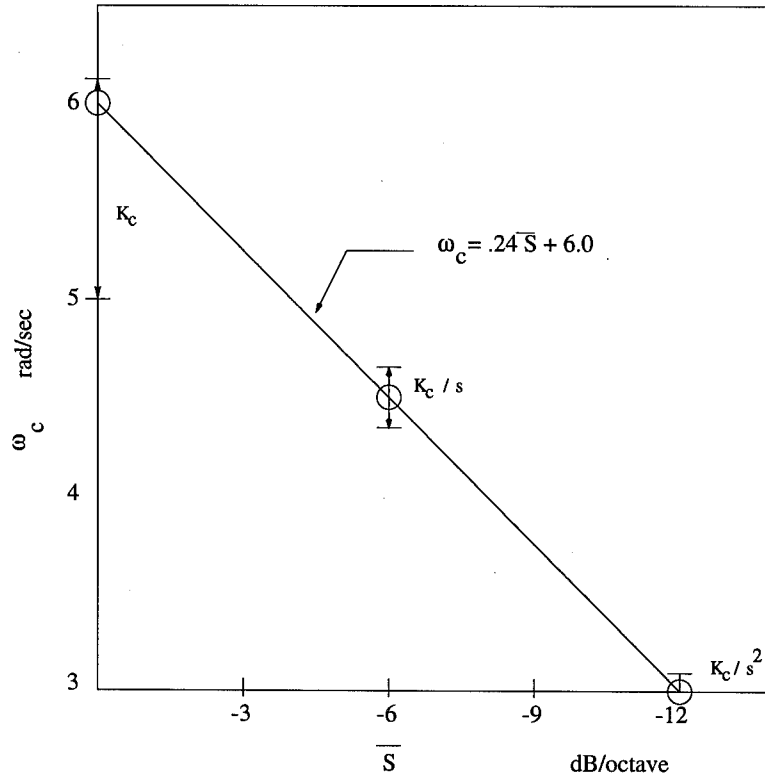


Figure 2.4: Specification of the Criterion Frequency

2.3 Time Domain Handling Qualities Criteria

The Time Domain criterion avoids the identification of dominant roots or equivalent systems models by working directly with the pitch rate transient response. Fig.(2.5) shows a typical pitch rate time history. The following measurements are defined [16, 1]:

- a. A horizontal line defining the steady-state pitch rate, q_{ss} .

b. A sloping straight line tangent to the pitch rate time history at the point of maximum slope. It is extended to intersect both the steady state line and the time axis.

c. Time t_1 measured from the instant the step input is applied to the time of intersection of the maximum-slope line with the time axis.

d. Time t_2 measured from the instant the step input is applied to the time corresponding to the intersection of the maximum-slope line with the steady-state line.

e. $\Delta q_1 \triangleq$ maximum pitch rate minus the steady state value

f. $\Delta q_2 \triangleq$ steady state minus time to the first minimum.

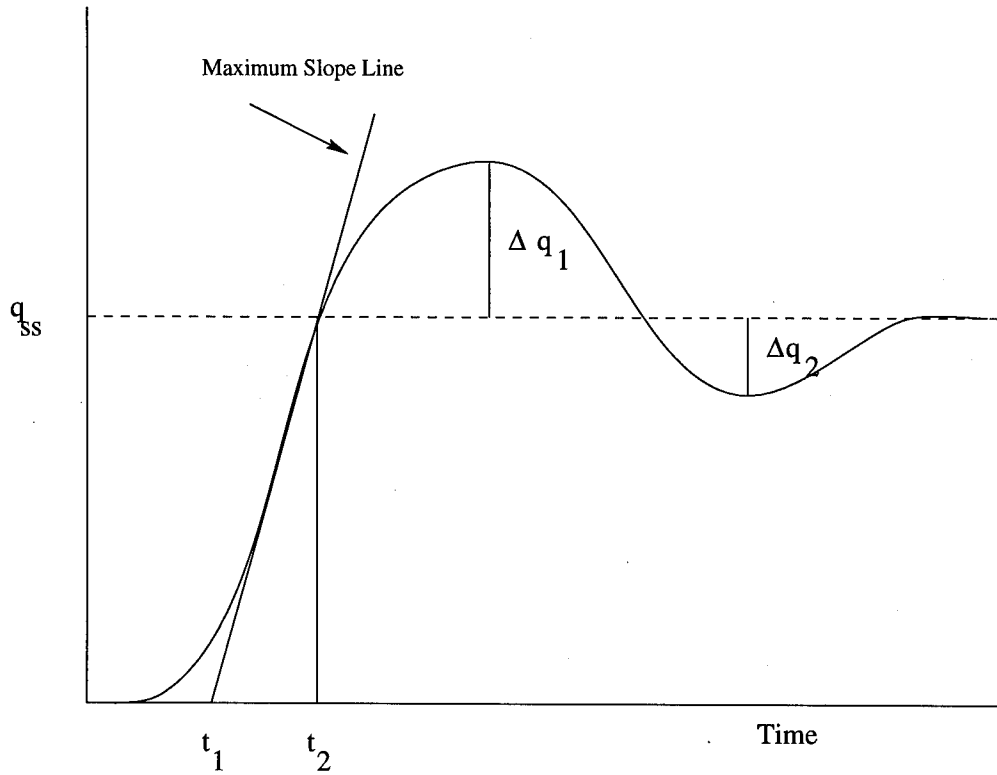


Figure 2.5: Pitch Rate Response to Step Input

The parameters defined above should meet the requirements described in the following subsections when a step input elevator deflection or a step stick force is applied.

2.3.1 Transient Peak Ratio, $\Delta q_2/\Delta q_1$

The Time Domain criterion are stated in terms of the transient peak ratio, $\Delta q_2/\Delta q_1$ or TPR. This is done to ensure that there is enough damping of the short period mode of the

pitch response. The specific values are based on the interpretation of short-period data in [17] and [18] and are shown in Table 2.2.

Table 2.2: Transient Peak Ratio, $\Delta q_2/\Delta q_1$, Levels

<i>Level</i>	<i>Maximum $\Delta q_2/\Delta q_1$</i>
1	$\leq .30$
2	$\leq .60$
3	$\leq .85$

2.3.2 Equivalent Time Delay, t_1

The time t_1 is considered the equivalent time delay and can be uniquely defined graphically, as seen in Fig.(2.5) [16]. In order to calculate t_1 , the x-intercept is determined from the equation of the line tangent to the maximum slope point. The limits shown in Table 2.3 [16] were determined by looking at flight test data from [19] and [20] for the terminal flight phase.

Table 2.3: Equivalent Time Delay, t_1 , Levels

<i>Level</i>	<i>Equivalent Time Delay</i>
1	$t_1 \leq .12\text{sec}$
2	$t_1 \leq .17\text{sec}$
3	$t_1 \leq .21\text{sec}$

2.3.3 Rise Time Parameter, Δt

The rise time parameter, Δt , is defined as

$$\Delta t = t_2 - t_1. \quad (2.10)$$

Table 2.4 shows the requirements that must be met for the rise time parameter for terminal flight phases. No Level 3 is defined. These limits are derived directly from the limits on $\omega_n^2/n/\alpha$ [16].

$$\frac{\omega_n^2}{n/\alpha} \equiv \frac{\dot{q}_{initial}}{n_{z_{ss}}} = \frac{q_{ss}/\Delta t}{q_{ss} \frac{V_T}{g}} = \frac{g}{V_T \Delta t} \quad (2.11)$$

The limits on $\omega_n^2/n/\alpha$ are defined as a function of the different flight phases [1]. Using these constant limits, it is easy to show that the boundaries for Δt are only a constant divided by the true airspeed. For example, for an aircraft in landing phase the Level 1 limits are

$$.16 \leq \frac{\omega_n^2}{n/\alpha} \leq 3.6 \quad (2.12)$$

Substituting in Eq.(2.11) and rearranging for Δt gives

$$\frac{g}{3.6V_T} \leq \Delta t \leq \frac{g}{.16V_T} \quad (2.13)$$

Table 2.4 [16] shows the limits that were derived from the data, with V_T in feet/second.

Table 2.4: Rise Time Parameter, Δt Levels

<i>Level</i>	<i>Minimum Δt</i>	<i>Maximum Δt</i>
1	$9/V_T$	$200/V_T$
2	$3.2/V_T$	$645/V_T$

2.4 Example Point

This section will consider one point and show how to determine the flying qualities level for both the Ralph Smith criterion and the Time Domain criterion. The sample transfer function is

$$\frac{\theta}{\delta_e} = \frac{(2.8553s + 2.445)e^{-.1s}}{s(s^2 + 9.5178s + 46.2182)} \quad (2.14)$$

Fig.(2.6) and Fig.(2.7) show the pitch rate response and Bode plots, respectively needed for this example. First, the pitch rate response is generated using a unit step input and time delay of .1 seconds. Next, a line representing the steady state value is drawn on the pitch rate history plot. Then a line tangent to the point of maximum slope is plotted. The time, t_1 is calculated by measuring the difference between the time the input is applied and the time the maximum slope line crosses the x axis. In this example, $t_1 = .1$ seconds. Recalling Table 2.3, this value has a rating of 1. The next step is to determine the time the maximum slope line crosses the steady state line. Subtracting t_1 from this value gives $\Delta t = .0185$. From Table 2.4 and $V_T = 65.23$ meters/second (214 feet/second), this corresponds to a

rating of 2. Now determine the transient peak ratio by computing Δq_1 , the maximum pitch rate minus the steady state value, and Δq_2 , the steady state value minus the first minimum value. Dividing Δq_2 by Δq_1 gives the transient peak ratio, $TPR = .0406$, and from Table 2.2 this has a rating of 1. The overall Time Domain handling qualities rating would be a Level 2, since Δt has the worst rating of the three parameters. Using the same pitch rate response, determine t_q , which is the time the maximum pitch rate occurs. For this example, $t_q = .2843$ seconds. From Table 2.1, this has a rating of 1. Looking at Fig.(2.7) determine the average slope of the magnitude plot on the frequency range of $1 \leq \omega \leq 6$ radians/second. This is determined by doing a least squares fit of the magnitude over the frequency range. For this example, $\bar{S} = -1.4$ dB/octave, which corresponds to a rating of 2. Now using Eq.(2.9) and the slope parameter from above, determine the criterion frequency. For this example $\omega_c = 5.66$ radians/seconds. Locate this frequency on the phase plot and to get the corresponding phase lag angle, $\angle_{\frac{\theta}{F_s}}(j\omega_c) = -116.35^\circ$. Once again looking a Table 2.1, this corresponds to a rating of 1. The overall Ralph Smith rating would be a Level 2, because the worst parameter rating is from \bar{S} . Table 2.5 summarizes the numerical value of the parameters and corresponding ratings, as well as the overall handling qualities level according to each of the criteria.

Table 2.5: Data For Example Point

<i>Time Domain Criterion</i>		
<i>Parameter</i>	<i>Value</i>	<i>Rating</i>
t_1	.1001 sec	1
Δt	.0185	2
$\Delta q_2/\Delta q_1$.0460	1
<i>Overall Level</i>		2
<i>Ralph Smith Criterion</i>		
<i>Parameter</i>	<i>Value</i>	<i>Rating</i>
t_q	.2843 sec	1
\bar{S}	-1.4 dB/oct	2
$\angle_{\frac{\theta}{F_s}}(j\omega_c)$	-116.35°	1
<i>Overall Level</i>		2

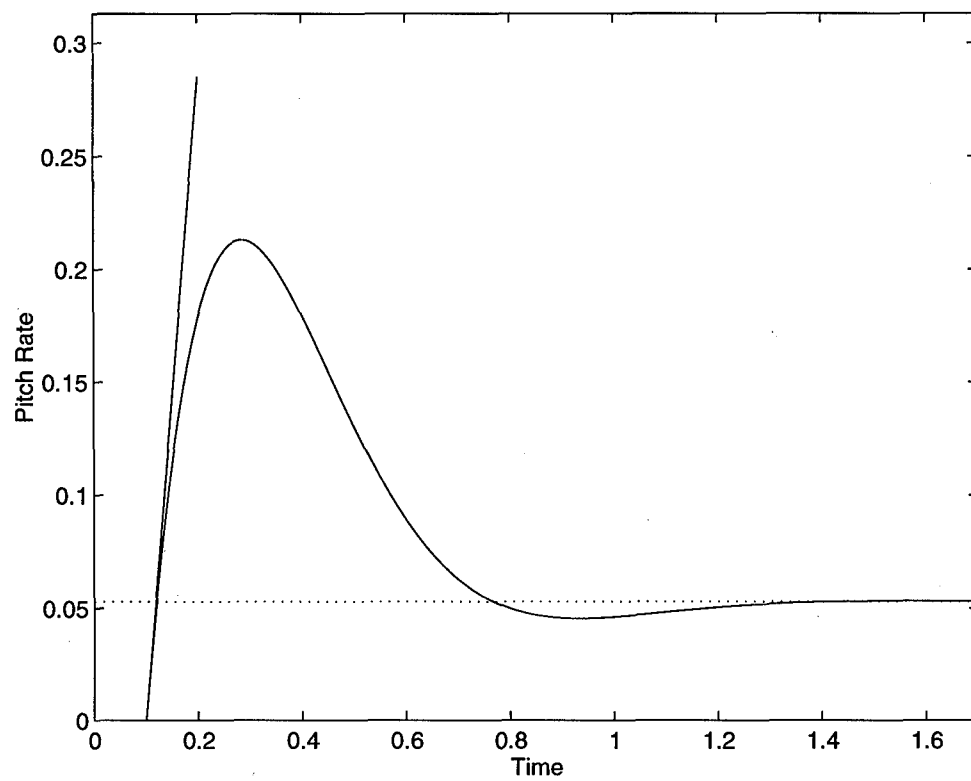


Figure 2.6: Pitch Rate Response for Example Point

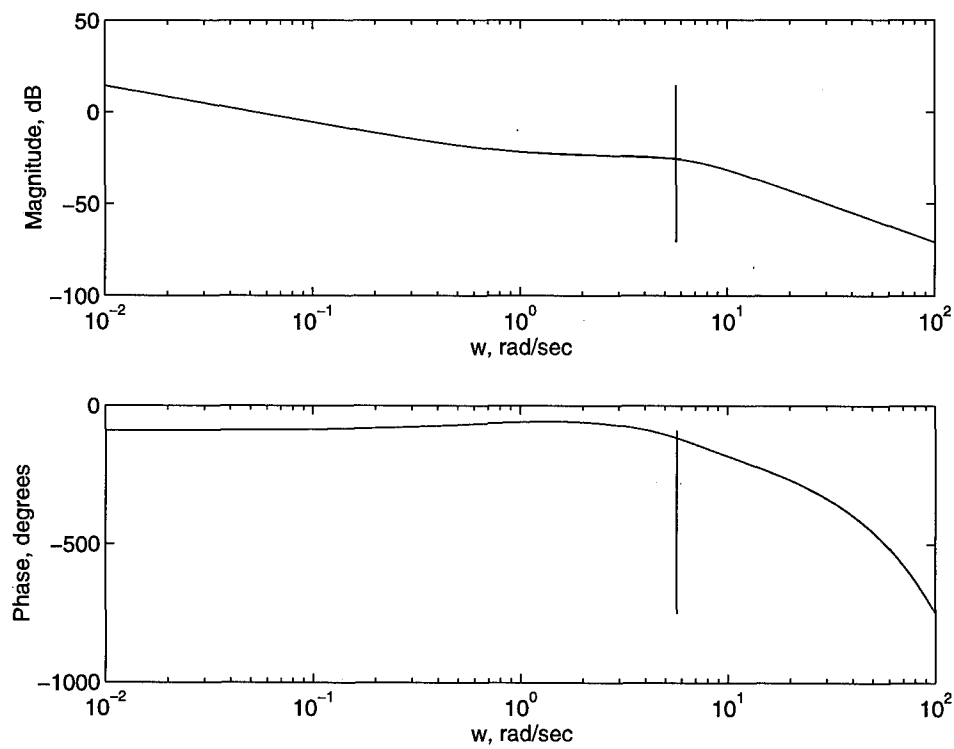


Figure 2.7: Bode Plot for Example Point

III. Results

This chapter outlines the approach that was used to map the criteria into each other and determine the areas of agreement and disagreement.

3.1 Basic Approach

In order to compare the Ralph Smith and Time Domain criteria it is necessary to look at both criteria in a common arena. Since both criterion require a pitch transfer function, the first step is to calculate the short period approximation of the $\frac{\theta}{\delta_e}$ transfer function. Recalling Eq.(2.3), it can be seen that there are five variables that need to be chosen, ω_{sp} , ζ_{sp} , T_{θ_2} , K_{θ} , and τ_{θ} . Of these parameters, three are set by the aircraft configuration. This leaves only ω_{sp} and ζ_{sp} to be determined. By varying these two parameters a grid can be set up and each criterion examined. Before going into the specific approach, there are two concerns that must be addressed. First, since both criteria specify boundaries for Level 3, it is likely that some aircraft configurations will fall outside of this level. Points that are labeled as loss of control, LOC, are those which do not fit the criteria bounds.

Another likely problem that can occur is in an over-damped system. This has two effects on the handling qualities level. First, an over-damped system causes a change in the definition of t_q , from the Ralph Smith criterion. This definition change can alter the predicted handling qualities level, by creating a discontinuity in the Level 1 region. The place where this definition change occurs is labelled, in this research, as the jump line. The other effect that an over-damped system has in the Time Domain criterion, with the transient peak ratio parameter. Recalling Section 2.3.1, TPR is used to ensure that there is enough damping in the pitch rate response. The parameter does not address what to do when the system is sluggish, or over-damped. Therefore, in this research TPR is neglected when evaluating an over-damped system and the flying qualities level is determined using the other two parameters.

3.2 Test Cases

Table 3.1 shows the 24 different test cases which were examined in this research. Every four cases represent a different aircraft transfer function and flight condition. Each flight condition is examined at four different time delays, τ_θ .

Table 3.1: Test Cases

Case	Height	Velocity	T_{θ_2}	K_θ	τ_θ	Remarks
	<i>m (ft)</i>	<i>m/s (ft/s)</i>			<i>s</i>	
1	304.8 (1000)	65.23 (214)	1.17	2.44	0	Learjet Transfer Function I
2					.1	
3					.15	
4					.2	
5	0	65.23 (214)	1.41	3.08	0	Learjet Transfer Function II
6					.1	
7					.15	
8					.2	
9	0	51.82 (170)	1.32	3.9897	0	Learjet Transfer Function III
10					.1	
11					.15	
12					.2	
13	1524 (5000)	77.11 (253)	2.12	.237	0	F-16 Transfer Function I
14					.1	
15					.15	
16					.2	
17	304.8 (1000)	65.23 (214)	1.69	.1144	0	F-16 Transfer Function II
18					.1	
19					.15	
20					.2	
21	30.48 (100)	64.2 (212)	1.77	.1431	0	F-16 Transfer Function III
22					.1	
23					.15	
24					.2	

3.3 Step By Step Process

This section will go through the steps required to create a mapping of each of the criteria. An example is provided to illustrate the algorithm. The example corresponds to Case 2 from Table 3.1. Results of all the cases examined are located in Appendix C.

Step 1: Fix aircraft and flight phase. This determines the aircraft classification and category. For this example, the Calspan Learjet 24, a Class II aircraft, will be chosen. The aircraft will be in a Category C flight phase, i.e. landing.

Step 2: Set the altitude, h , and the velocity, V_T . This is needed to find the non-dimensional stability derivatives which correspond to the flight condition. The example has the aircraft at a height of 304.8 meters (1000 feet) and a velocity of 65.23 m/sec (214 ft/sec).

Step 3: Determine T_{θ_2} and K_{θ} from the non-dimensional stability derivatives and Eq.(2.2). These two variables only effect the numerator of the transfer function. Therefore,

$$N_{\delta_e}^{\theta} = 2.44(1.17s + 1) \quad (3.1)$$

Step 4: Fix the time delay, τ_{θ} . For the example, $\tau_{\theta} = .1$ seconds.

Step 5: Determine the Ralph Smith criterion for a grid of transfer functions by varying ω_{sp} and ζ_{sp} . This research used a grid of 10,000 points to determine the criterion as was previously discussed in the example point in Chapter II. Fig.(3.1) shows the result of this step for the example.

Step 6: Determine the Time Domain criterion in a similar manner, as seen in Fig.(3.2).

Step 7: Cross plot each level to show the areas of agreement and conflict. Fig.(3.3) shows the comparison of the Level 1 regions. The Level 2 regions are compared in Fig.(3.4). The Level 3 comparison is shown in Fig.(3.5), while Fig.(3.6) compares the two loss of control regions for this example.

The computer code that resulted from the algorithm was written for MATLABTM and is shown in Appendix D. It examines the two criteria for a grid of 10,000 points.

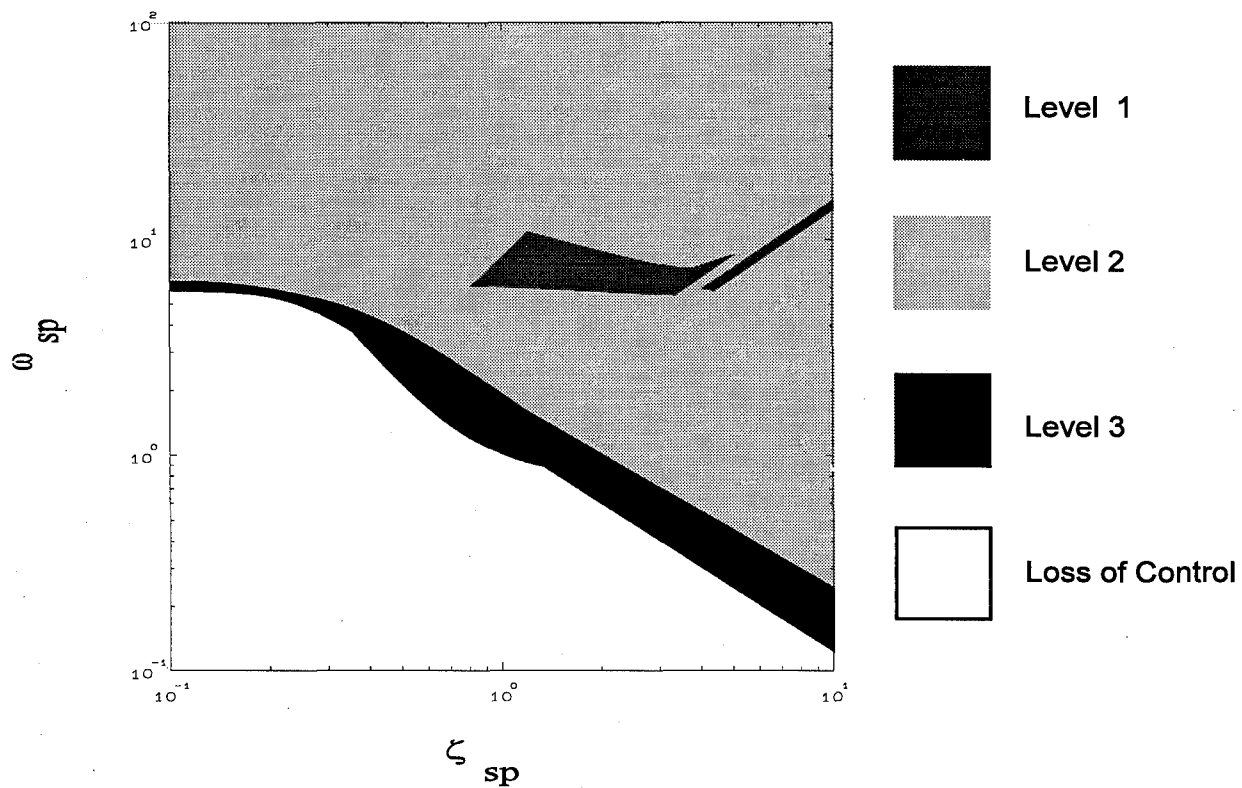


Figure 3.1: Ralph Smith Criterion for Learjet Example

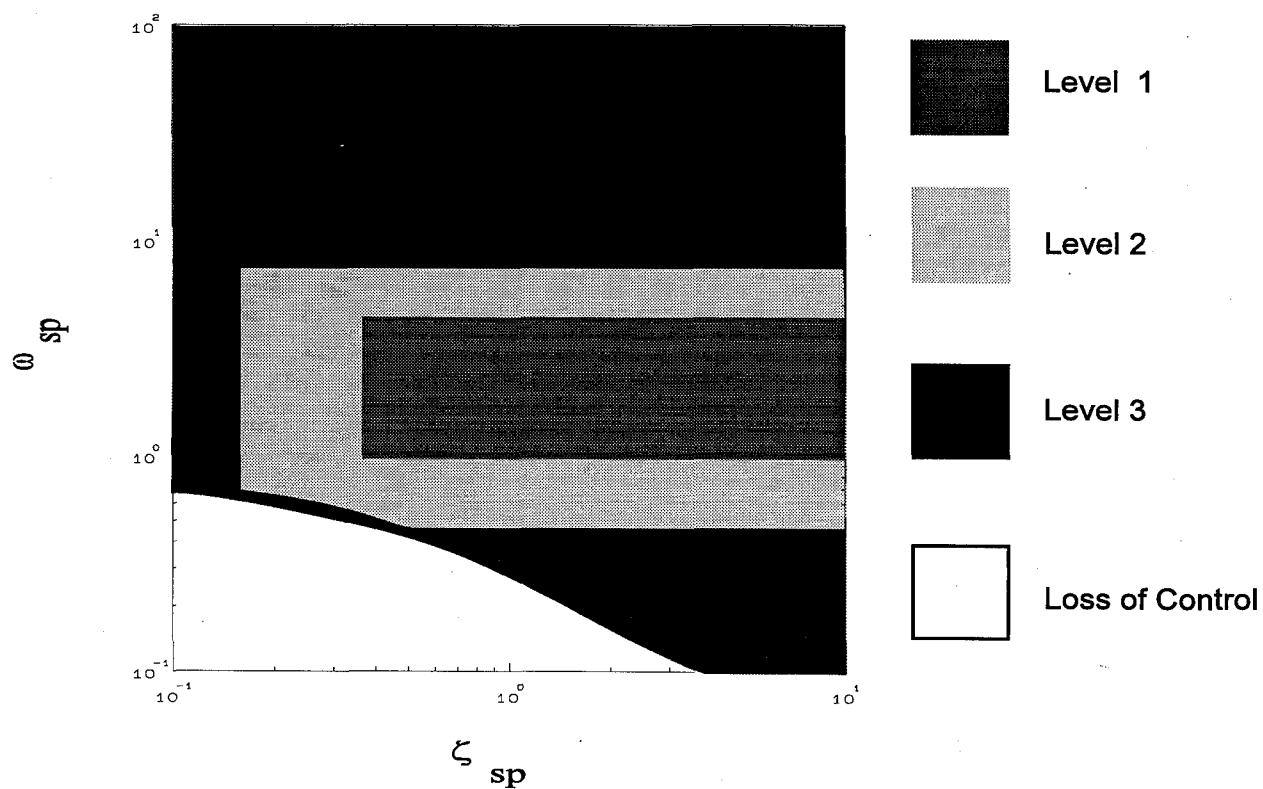


Figure 3.2: Time Domain Criterion for Learjet Example

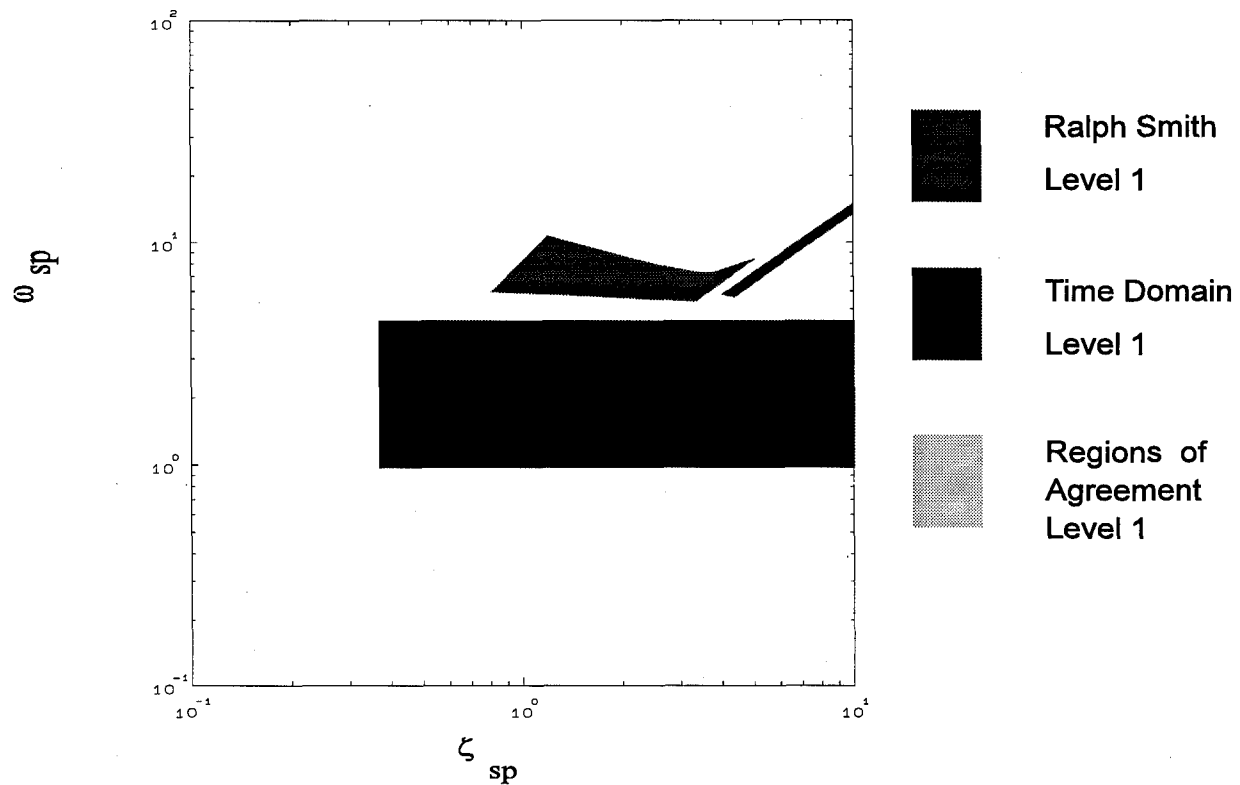


Figure 3.3: Level 1 Comparison for Learjet Example

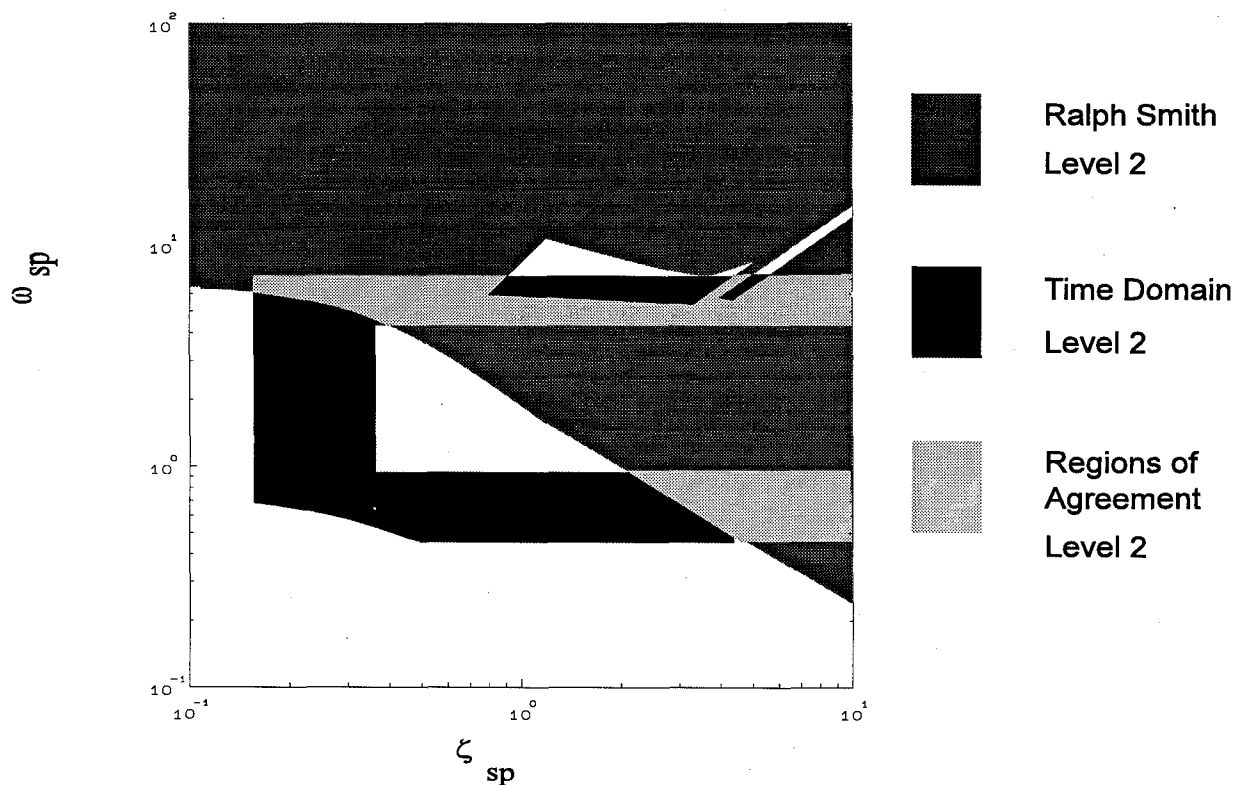


Figure 3.4: Level 2 Comparison for Learjet Example

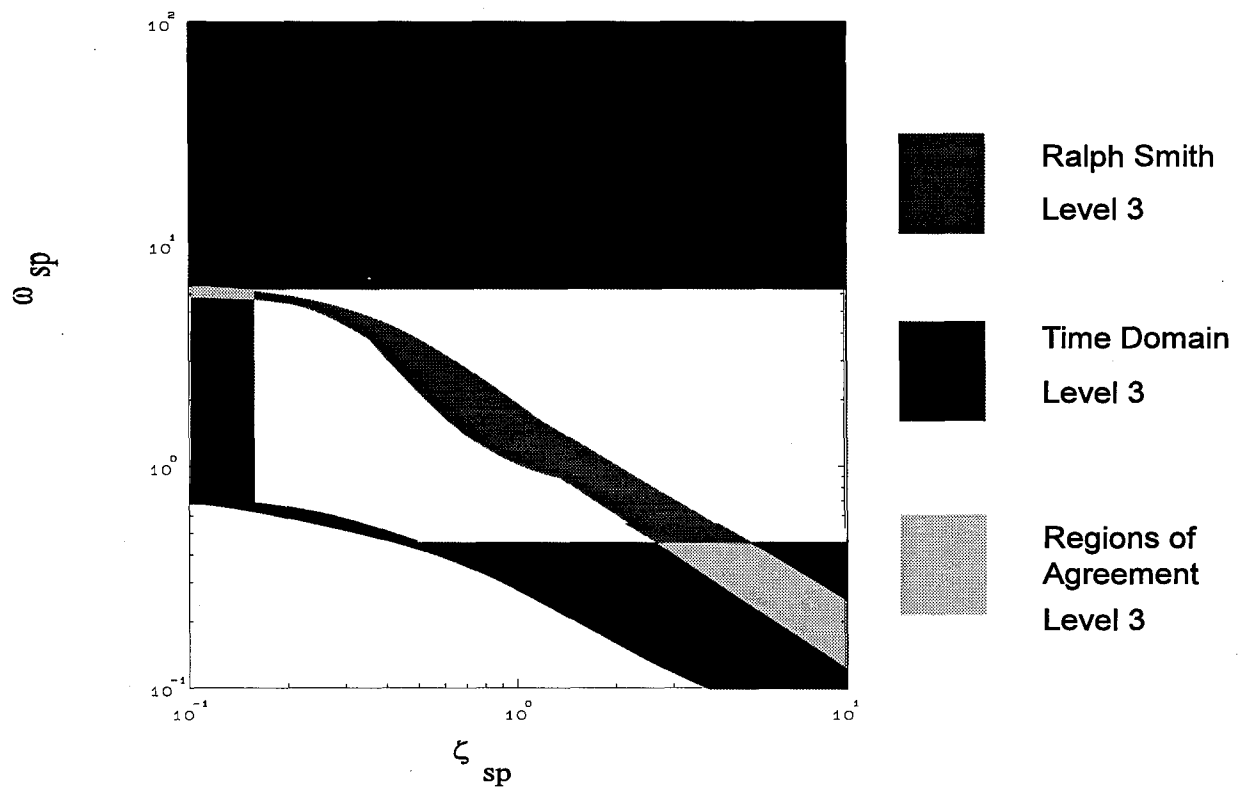


Figure 3.5: Level 3 Comparison for Learjet Example

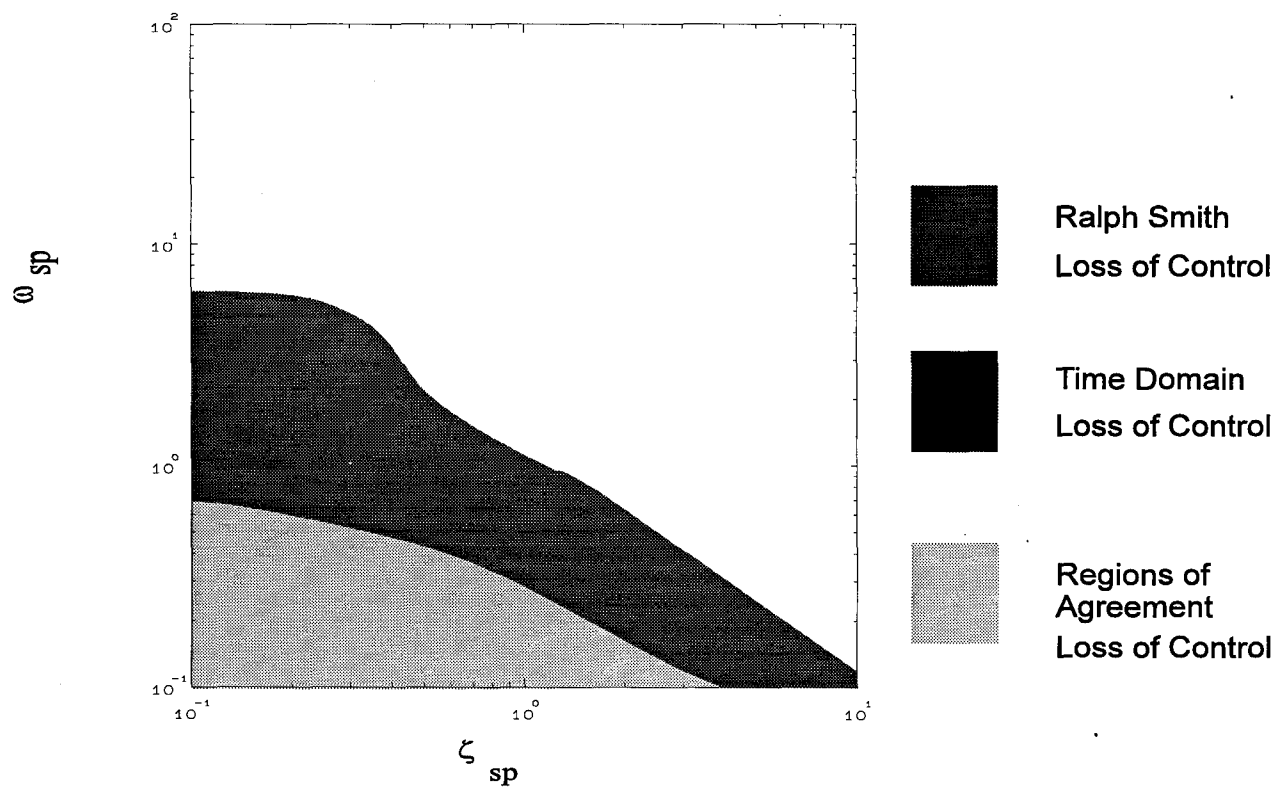


Figure 3.6: Loss of Control Region Comparison for Learjet Example

IV. Analysis

One objective of this research was to examine trends resulting from changing parameters. This chapter will examine the results from that study.

4.1 Ralph Smith Boundaries

Fig.(4.1) shows where each of the definitions of the Ralph Smith criterion take effect. It can be seen that only Level 1 has multiple boundaries. This is because it is the only level with definitions in all three parts of the criterion.

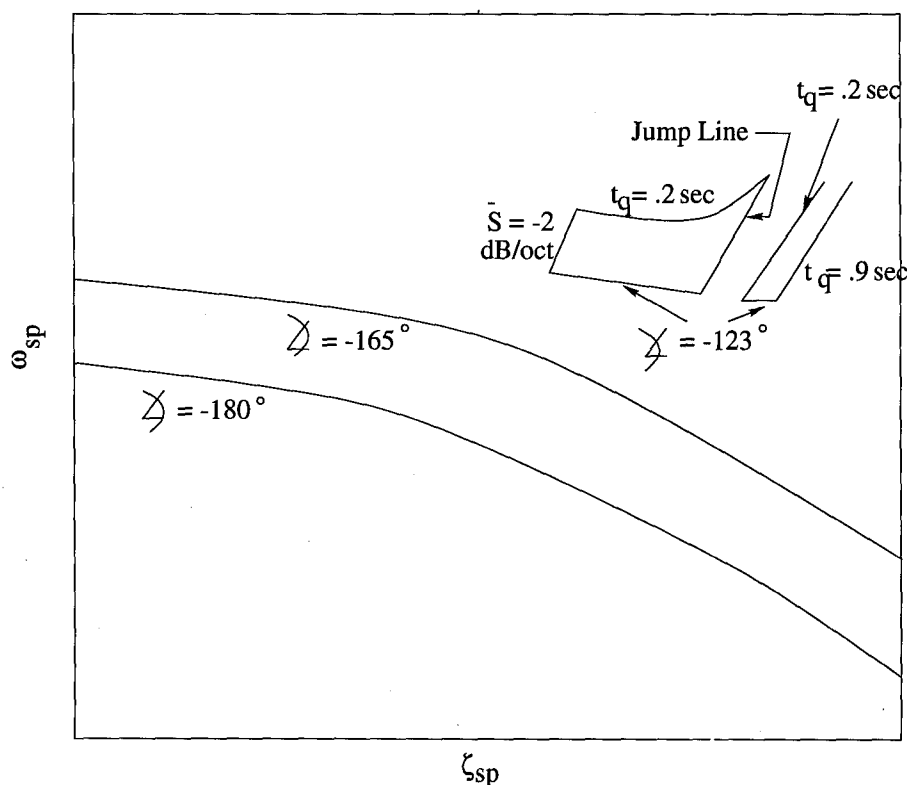


Figure 4.1: Ralph Smith Boundaries

The jump line, as seen in Fig.(4.1), is the boundary which separates the two definitions of the time to first peak, t_q . The value of t_q never goes to any particular value, but *jumps* from the one definition to the next, thus changing the flying qualities level. This jump line is the beginning of the discontinuity which is present in the Level 1 region. As ζ_{sp} increases, the pitch rate response becomes over-damped. The Ralph Smith criterion states that for an over-damped system t_q is no longer defined as time to first peak, but as the time to 90% of

the steady state value. Once the definition changes, the pitch rate response is over-damped, and t_q , using the new definition, becomes smaller than the minimum bound. Continuing to increase ζ_{sp} increases t_q so it is within the Level 1 boundary, temporarily. Ultimately, the pitch rate response gets too slow for a Level 1 rating and is given a Level 2, since no other limits are defined. An example of two transfer functions on either side of the jump line is shown below.

$$\frac{\theta(s)}{\delta_e(s)} = \frac{(2.8533s + 2.445)e^{-.1s}}{s(s^2 + 41.793s + 36.238)} \quad (4.1)$$

and

$$\frac{\theta(s)}{\delta_e(s)} = \frac{(2.8533s + 2.445)e^{-.1s}}{s(s^2 + 43.346s + 36.238)} \quad (4.2)$$

both represent aircraft transfer functions, with the same numerator and ω_{sp} . The only difference is in the short period damping ratio: $\zeta_{sp1} = 3.4713$ while $\zeta_{sp2} = 3.6003$. Fig.(4.2) and Fig.(4.3) show the pitch rate response for Eq.(4.1) and Eq.(4.2), respectively. By changing ζ_{sp} , the pitch rate response goes from having an overshoot and a rating of 1, to being over-damped with a rating of 2.

4.1.1 Effects of Changing τ_θ on the Ralph Smith Criterion

This section will examine the effect that changing the time delay, τ_θ , has on the Ralph Smith criterion. The levels will be broken down into two areas of discussion. The first one describes the transformation of the Level 1 region as τ_θ is increased, while the other discusses the Level 2 and 3 regions.

Fig.(4.4) shows the Ralph Smith criterion Level 1 region as it transforms with changing time delay, τ_θ . When $\tau_\theta = 0$ seconds the region shows that the previously mentioned discontinuity is present, but not completely visible. As τ_θ is increased to .1 seconds, the discontinuity is larger and the entire level 1 region is moved upward and to the right. The lower boundary, set by $\angle \frac{\theta}{F_s}(j\omega_c)$ rotates slightly counter-clockwise. Increasing τ_θ to .15 seconds removes the discontinuity completely. The reason for this is that the system is no longer receiving a rating of 1 in the phase lag parameter when the definition of t_q changes, thus there is no longer a jump line. Once the jump line and discontinuity disappear, only

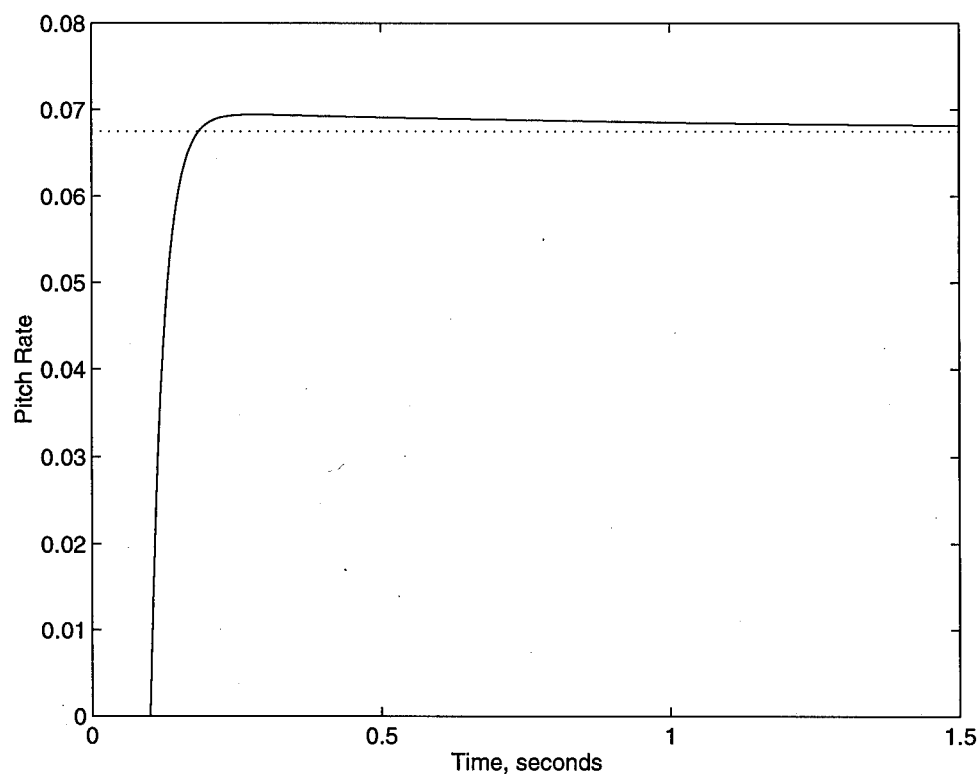


Figure 4.2: Pitch Rate Response for Eq.(4.1)

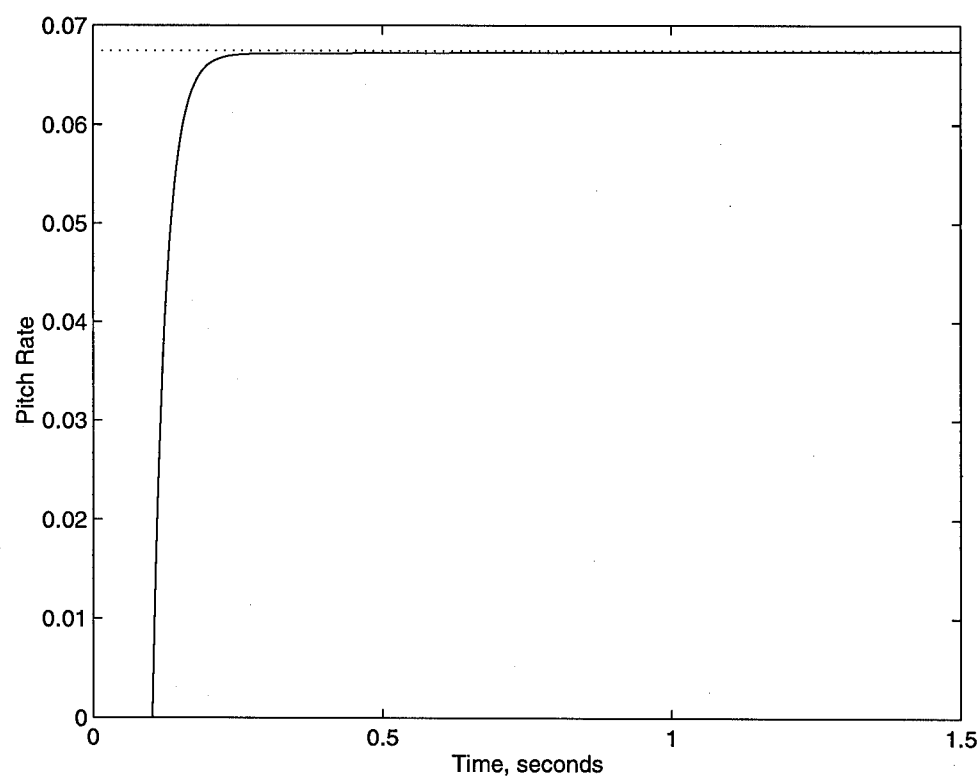


Figure 4.3: Pitch Rate Response for Eq.(4.2)

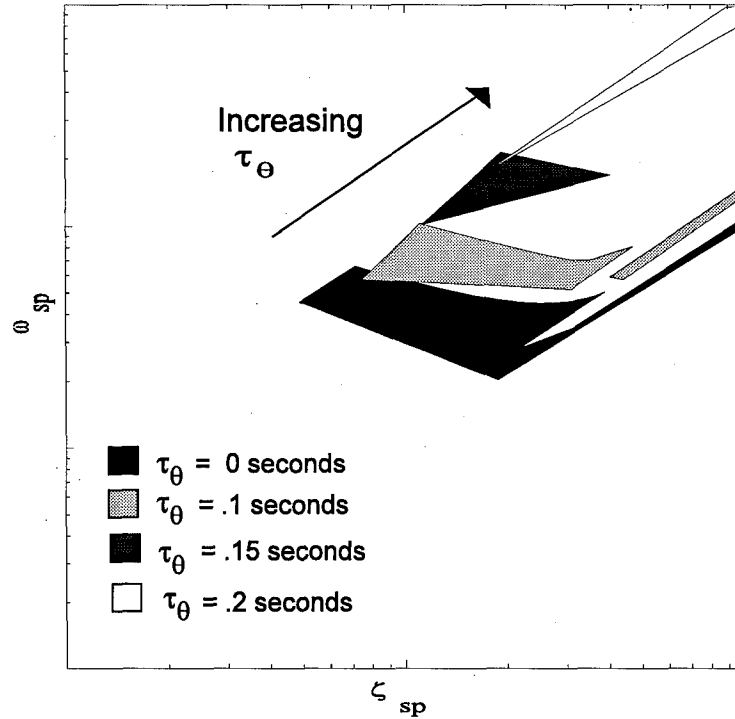


Figure 4.4: Effect of Changing τ_θ on Level 1

three boundaries are left in this region. When τ_θ is increased to .2 seconds, the region rotates in a similar fashion, while the $t_q = .2$ boundary is no longer present.

Fig.(4.5) is the transformation of the Level 2 and Level 3 regions as a result of changing τ_θ . In order to avoid confusion the Level 1 region is omitted in since the boundaries change in the same manner as seen in Fig.(4.4). Both the lower Level 2 boundary and the Level 3 boundaries are defined by one parameter, $\angle \frac{\theta}{F_s}(j\omega_c)$. Since a time delay is represented on a the Bode plots as $-\tau_\theta\omega$, meaning the phase angle decreases as a function of the frequency, ω . This phase angle is added to the angle of the transfer function without the time delay, to get the total phase angle. This means that as τ_θ increases, the phase lag parameter decreases. The more lag in the system, the worse the handling qualities become, thus moving the boundaries of the Level 2 and Level 3 regions for the Ralph Smith criterion.

4.1.2 Effect of Changing T_{θ_2} on the Ralph Smith Criterion

For $\tau_\theta = .1$ seconds, as T_{θ_2} increases, the lower boundary of the Level 3 region changes, as shown in Fig.(4.6). The bulge in the region moves upward and increases in size as T_{θ_2} increases.

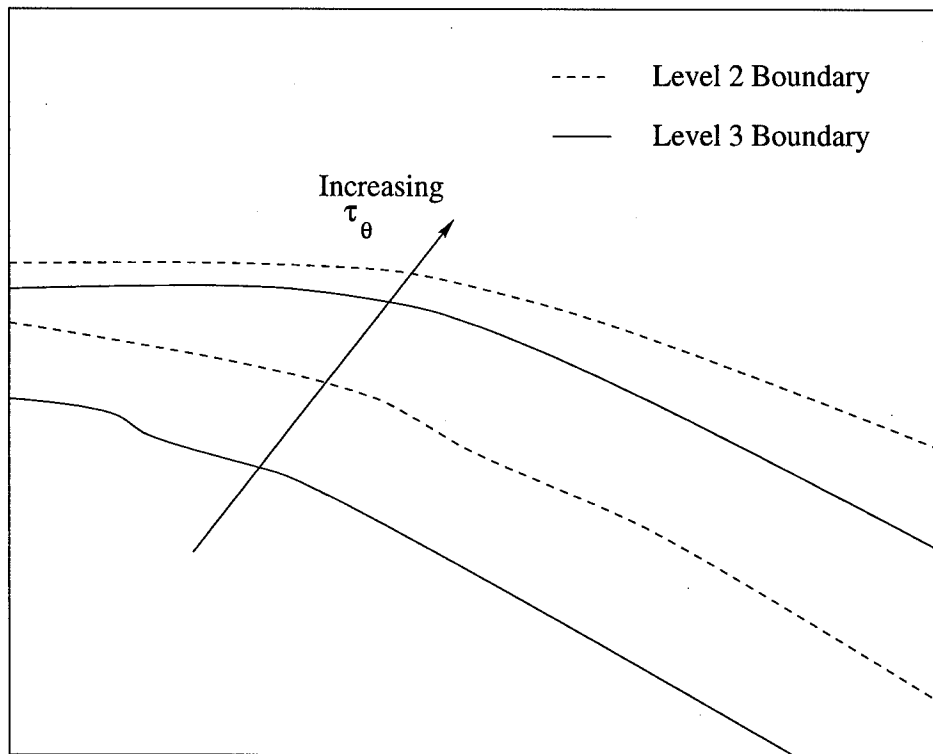


Figure 4.5: Effect of Changing τ_θ on Level 2 and Level 3

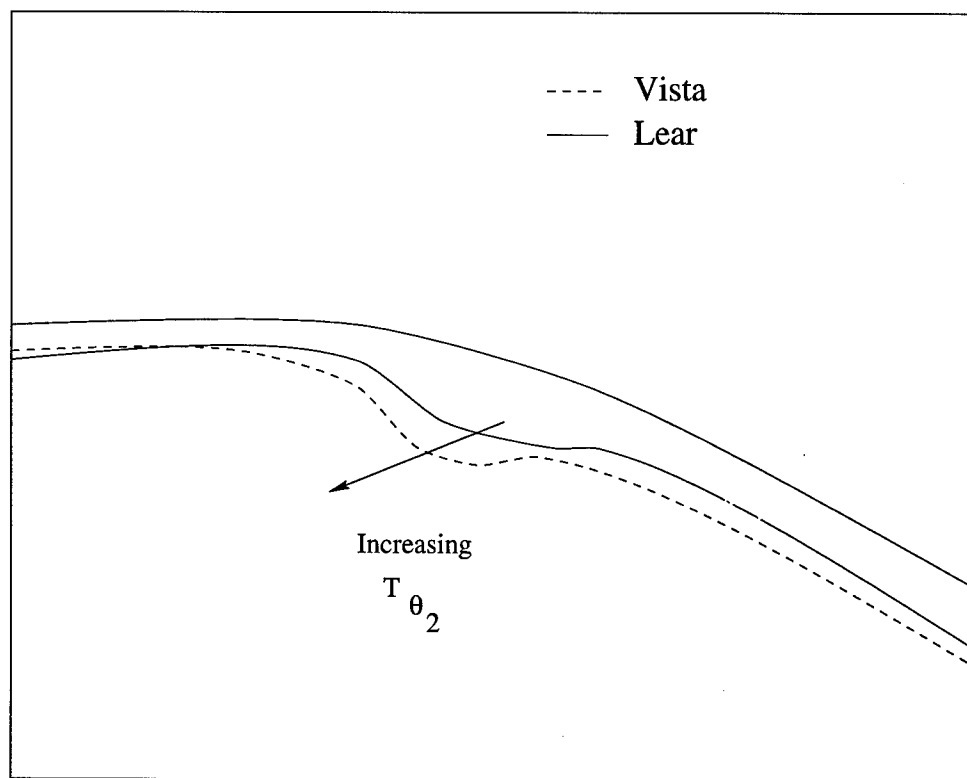


Figure 4.6: Effect of Changing T_{θ_2} on the Ralph Smith Criterion

4.2 Time Domain Boundaries

Fig.(4.7) shows where each of the definitions of the Time Domain criterion take effect.

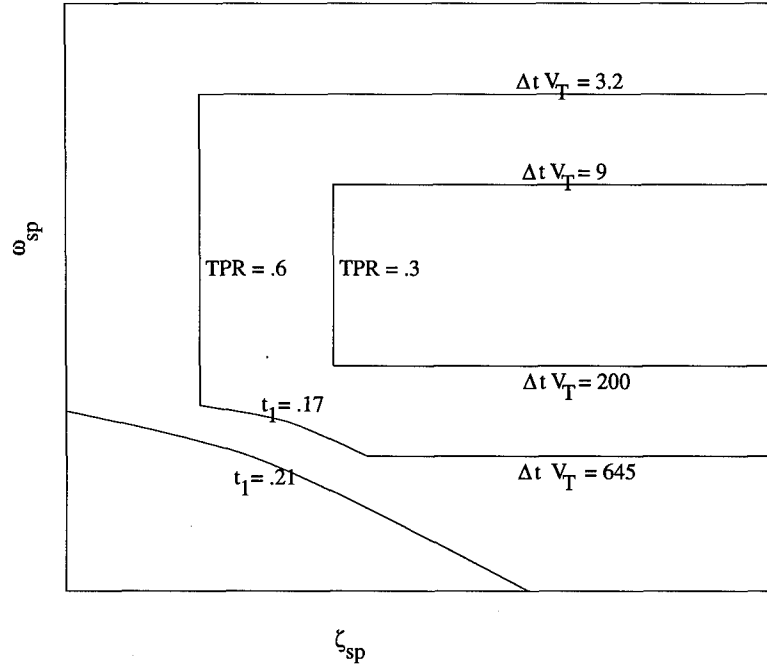


Figure 4.7: Time Domain Boundaries

4.2.1 Effects of Changing τ_θ on the Time Domain Criterion

The effective time delay, t_1 , corresponds to the time delay, τ_θ , by the following relationship.

$$\tau_\theta \approx t_1 \quad (4.3)$$

This corresponds to the curved boundaries on the lower left of both level 2 and level 3. The effect of changing the time delay can be seen in Fig.(4.8). Since τ_θ emulates t_1 , when the time delay is increased beyond the equivalent time delay boundaries defined in Table 2.3, the rating of t_1 changes. This in turn completely eliminates the lower handling qualities level. When $\tau_\theta \leq .12$ seconds all the regions are present. If $.12 < \tau_\theta \leq .17$ seconds, the entire Level 1 region has disappeared, as shown in Fig.(4.8-B), leaving Level 2 ratings in its place. At $\tau_\theta > .17$ seconds, the Time Domain criterion no longer gives a region of Level 2, Fig.(4.8-C). Increasing the time delay greater than .21 seconds, leaves only a loss of control region, since the Level 3 region disappears.

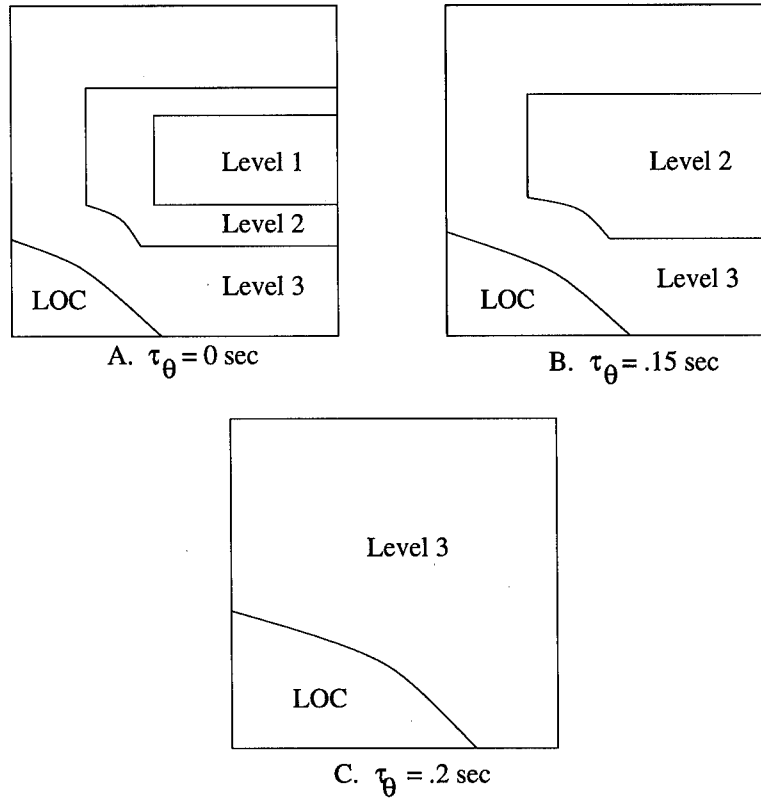


Figure 4.8: Effect of τ_{θ} on Time Domain Criterion

4.2.2 Effect of Changing T_{θ_2} on the Time Domain Criterion

If τ_{θ} is held constant while varying T_{θ_2} , the Time Domain Level 1 and Level 2 shift the upper and lower boundaries. From MIL-STD-1797A, there exists a relationship between ω_{sp} and Δt [1].

$$CAP = \frac{\omega_{sp}^2}{n/\alpha} \approx \frac{g}{V_T \Delta t} \quad (4.4)$$

CAP, the Control Anticipation Parameter, is related to ω_{sp} by

$$CAP \approx \frac{\omega_{sp} g}{V_T} (\omega_{sp} T_{\theta_2}) \quad (4.5)$$

By substituting in the boundary values given for Δt , the boundaries in ω_{sp} can be approximated.

Rearranging for ω_{sp} in terms of Δt ,

$$\omega_{sp} \approx \sqrt{\frac{1}{T_{\theta_2} \Delta t}} \quad (4.6)$$

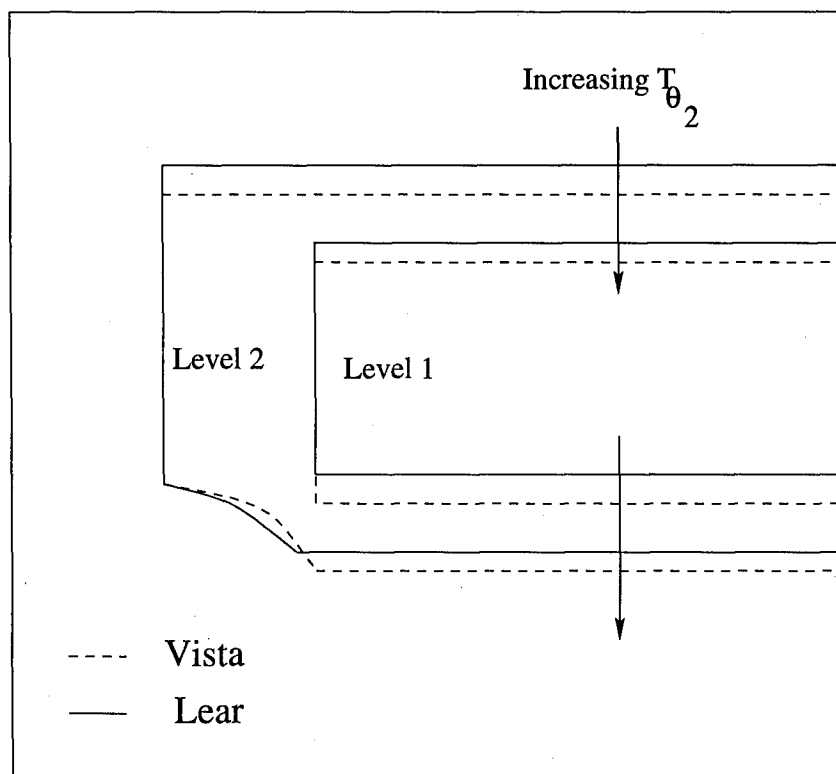


Figure 4.9: Effects of Changing T_{θ_2} on the Time Domain Criterion

By substituting in the boundaries for Δt , it turns out that the upper boundary value for Δt is the lower boundary in ω_{sp} and vice versa. Using this relationship it is possible to see that when T_{θ_2} is increased the boundaries are expanded, as shown in Fig.(4.9).

4.2.3 Relationship between TPR and ζ

From MIL-STD-1797A, the relationship between transient peak ratio and ζ_{sp} , for the classical aircraft response, is shown in Table 4.1 [1]. The limits on TPR correspond to the lower bounds on ζ_{sp} . They are fixed for all values of τ_{θ} and T_{θ_2} .

Table 4.1: Corresponding Damping Ratios for Transient Peak Ratios

Level	$\Delta q_2/\Delta q_1$	ζ
1	.30	.36
2	.60	.16
3	.85	.052

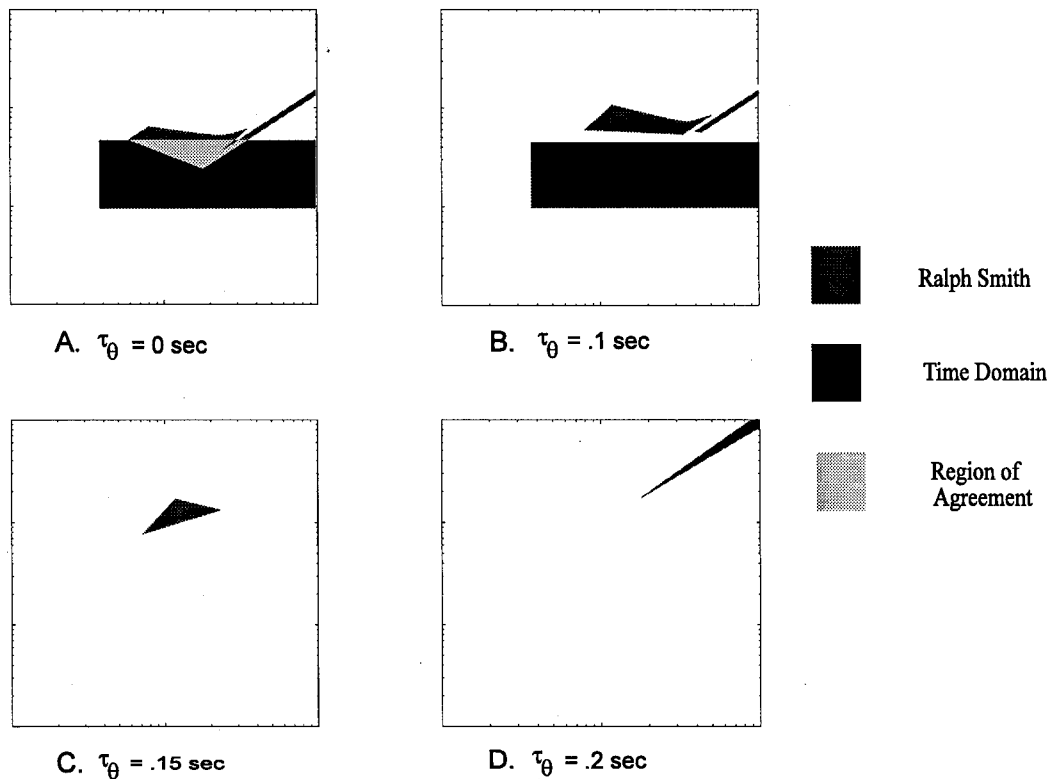


Figure 4.10: Comparison of Level 1 Regions

4.3 Comparison

This section will do a general comparison of the Ralph Smith criterion to the Time Domain Criterion.

4.3.1 Level 1 Regions

The area of agreement for Level 1 is dependent upon the value of τ_θ . The only agreement between the Ralph Smith criterion and the Time Domain Criterion occurs when $\tau_\theta = 0$ seconds. This region of agreement can change with T_{θ_2} as seen in Section 4.2.2. As τ_θ increases, the region of agreement no longer exists. There are two reasons explaining this trend. First, as described in Section 4.1.1, the Ralph Smith criterion Level 1 region shifts as the time delay increases. The effect of this shifting moves the two regions away from each other. Next, when τ_θ becomes greater than .12 seconds, there is no longer a Time Domain Level 1 and therefore no agreement. The entire transformation of the Level 1 region of agreement is shown in Fig.(4.10) for increasing τ_θ .

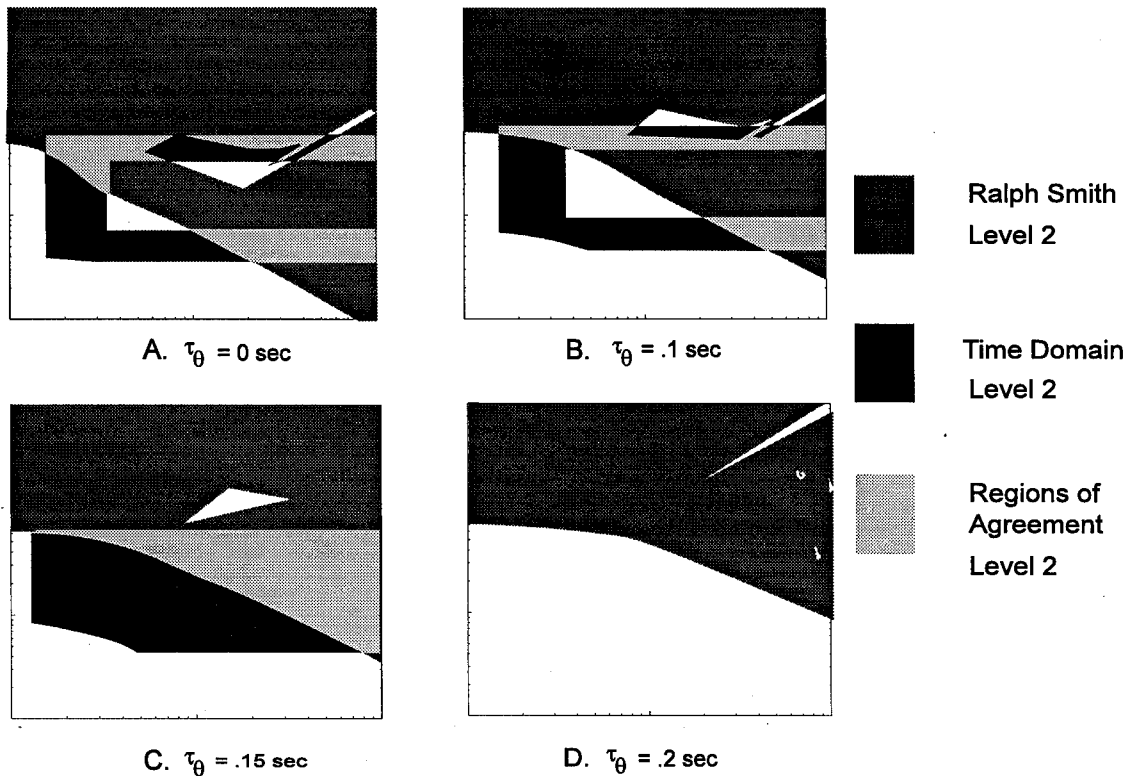


Figure 4.11: Comparison of Level 2 Regions

4.3.2 Level 2 Regions

The Level 2 region of agreement can consist of discontinuous area, depending on the value of τ_θ . When $\tau_\theta = 0$, the regions of agreement consist of four distinct areas. This is because the Level 1 regions are present and overlapping, Fig.(4.11-A). If $\tau_\theta = .1$ seconds, Fig.(4.11-B) shows that there are two regions of agreement. This again is due to the presence of the Level 1 regions. After τ_θ becomes greater than .12 seconds, there is only one region of agreement, since all of the Time Domain Level 1 has disappeared seen in Fig.(4.11-C). At $\tau_\theta > .17$ seconds there is no agreement between the criteria in Level 2, Fig.(4.11-D), since the Time Domain no longer has a Level 2 region.

4.3.3 Level 3 Regions

In a similar manner to the Level 2 region of agreement, Level 3 has a discontinuous agreement area. Fig.(4.12) shows the transformation of the area as τ_θ increases. The largest amount of agreement between the criteria exists when $\tau_\theta = .2$ seconds, at this condition all of Ralph Smith Level 3 maps into Time Domain Level 3, seen in Fig.(4.12-D).

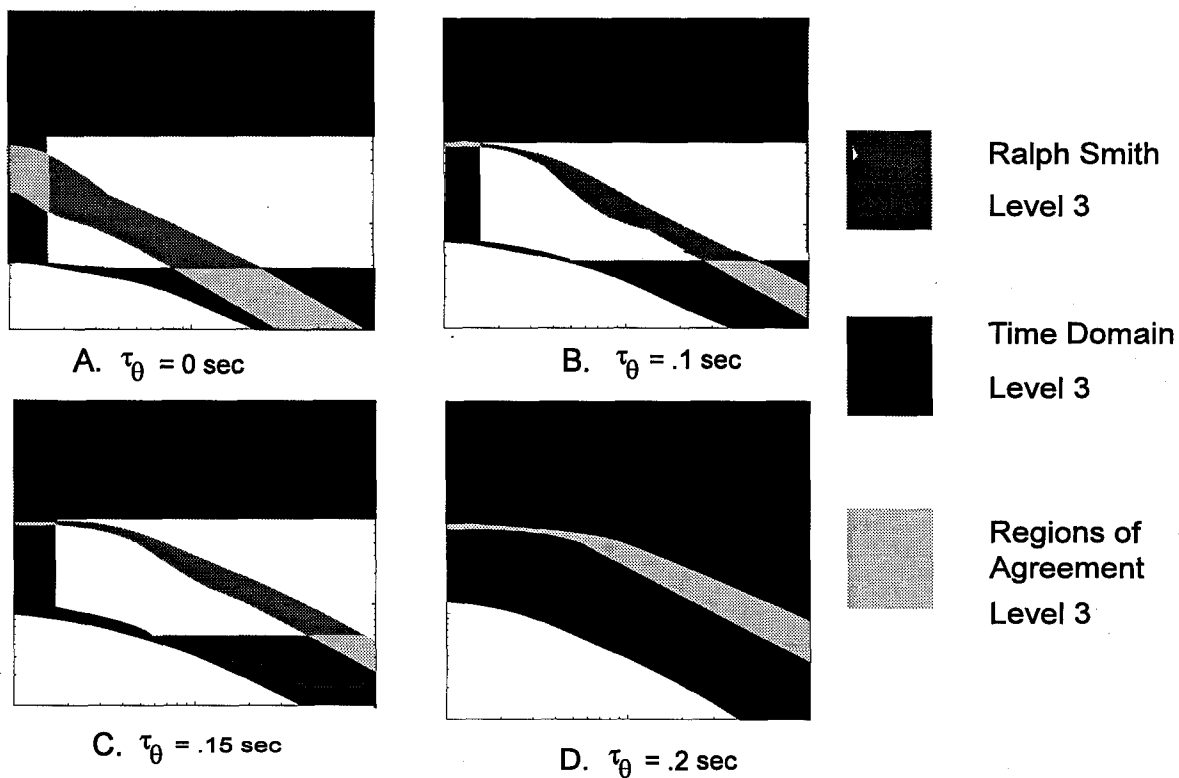


Figure 4.12: Comparison of Level 3 Regions

4.3.4 Loss of Control Regions

All of the Time Domain criterion that is rated as LOC maps directly into the Ralph Smith region of LOC. Fig.(4.13) is representative of the mapping for the loss of control region at all τ_θ .

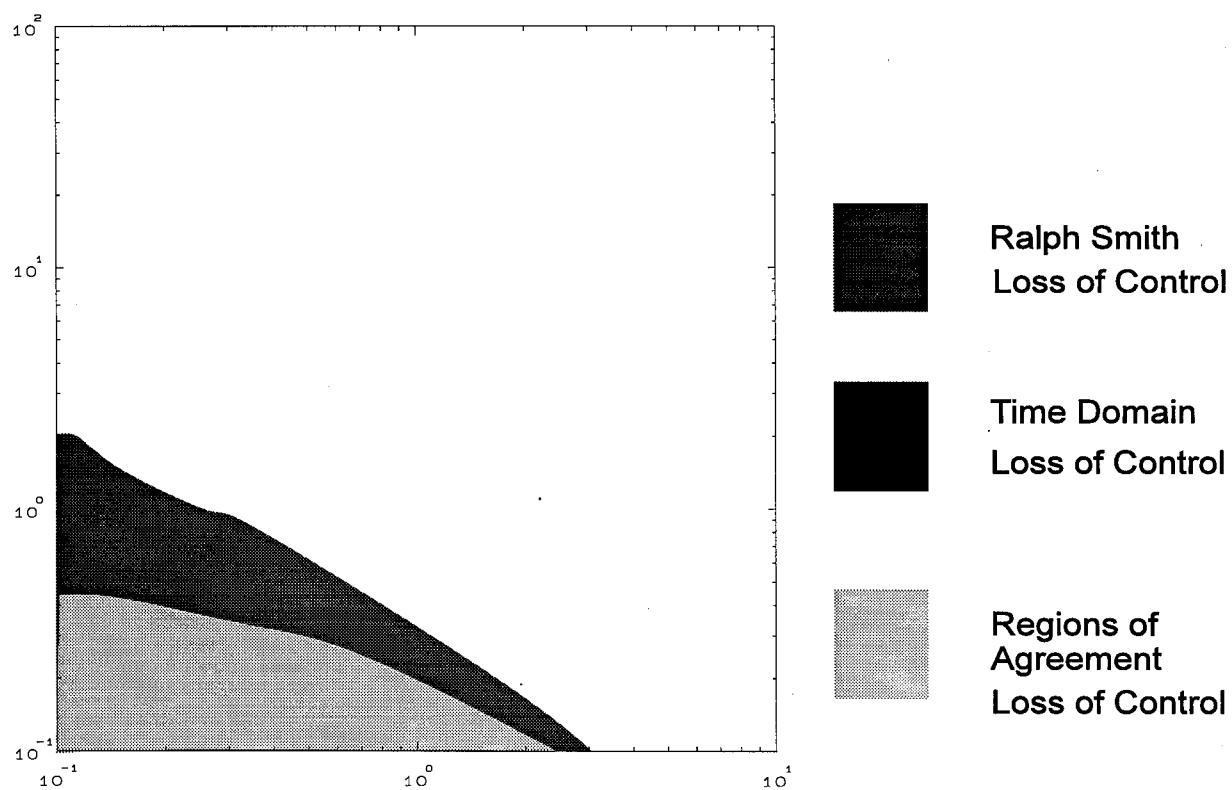


Figure 4.13: Comparison of Loss of Control Regions

V. Conclusions and Recommendations

5.1 Conclusions

All the objectives for this research were accomplished. First a computer code was developed to determine the handling qualities level for both the Ralph Smith criterion and the Time Domain criterion, simultaneously. The code allows a grid of transfer functions to be analyzed for a set aircraft. A system for mapping the areas of agreement and disagreement was then developed. By systematically tagging each point on the grid, the conflicting regions, as well as the regions of agreement could be identified.

With the cases examined in this research, a general comparison between the Ralph Smith criterion and the Time Domain criterion can be discussed. The best comparison of the two criteria is in the Loss of Control region. Here all points defined as LOC in the Time Domain criterion are also LOC in the Ralph Smith criterion, regardless of the time delay. The only other time that all points of one criterion mapped directly into another is the Level 3 region of the Ralph Smith criterion when the time delay is equal to .2 seconds. This is because the Time Domain criterion only consists of a Level 3 region and a LOC region. Looking at the rest of the cases show that there is little agreement between the two criteria, especially in the Level 1 region, since the Time Domain criterion has no Level 1 region after $\tau_\theta > .12$ seconds. Therefore, the analysis of the results show that the Ralph Smith criterion and the Time Domain criterion have very little in common.

One way to increase the area of agreement between these two criteria is to modify the Ralph Smith criterion in order to loosen the boundaries on the phase lag parameter. By doing this, the Level 1 region can be increased to include more area. A modification that can be made to the Time Domain criterion is to change the rise time parameter bounds. By decreasing the minimum boundaries and increasing the maximum boundaries, the Level 1 and 2 regions can be increased to allow more comparability between the aircraft.

5.2 Recommendations for Future Research

The results produced by this research lay another brick in the foundation started by Kish and Kivioja, though this is not the end. Further research can be done on the different flight phase categories. Selected points from any region of conflict could be flown in a flight test program to determine the actual handling qualities. Flight testing some points can determine the true flying qualities level, since the aircraft is a nonlinear system with a pilot and the results of this research is for a linear approximation. The results could then be analyzed to determine whether the Ralph Smith or Time Domain criteria need to be refined, combined, or even completely eliminated.

Appendix A. Derivation of K_θ

This section will show the derivation of K_θ used in the short period approximation of the pitch transfer function. The derivation uses the dimensional stability derivatives, which are unique for aircraft and flight conditions.

$$\frac{\theta}{\delta_e} = \frac{(U_1 M_{\delta_e} + Z_{\delta_e} M_{\dot{\alpha}})s + (M_\alpha Z_{\delta_e} - M_{\delta_e} Z_\alpha)}{U_1 s(s^2 - (\frac{Z_\alpha}{U_1} + M_q + M_{\dot{\alpha}})s + (\frac{M_q Z_\alpha}{U_1} - M_\alpha))} \quad (\text{A.1})$$

Since $Z_{\delta_e} M_{\dot{\alpha}} \ll U_1 M_{\delta_e}$, $Z_{\delta_e} M_{\dot{\alpha}}$ can be ignored. Therefore,

$$\frac{\theta}{\delta_e} = \frac{U_1 M_{\delta_e} s - M_{\delta_e} Z_\alpha + M_\alpha Z_{\delta_e}}{U_1 s(s^2 - (\frac{Z_\alpha}{U_1} + M_q + M_{\dot{\alpha}})s + (\frac{M_q Z_\alpha}{U_1} - M_\alpha))} \quad (\text{A.2})$$

Now define

$$\omega_{sp}^2 \triangleq \frac{M_q Z_\alpha}{U_1} - M_\alpha \quad (\text{A.3})$$

$$\zeta_{sp} \triangleq \frac{-(\frac{Z_\alpha}{U_1} + M_q + M_{\dot{\alpha}})}{2\sqrt{\frac{M_q Z_\alpha}{U_1} - M_\alpha}} \quad (\text{A.4})$$

$$\frac{1}{T_{\theta_2}} \triangleq \frac{M_\alpha Z_{\delta_e} - M_{\delta_e} Z_\alpha}{U_1 M_{\delta_e}} \quad (\text{A.5})$$

Substituting in the above definitions,

$$\frac{\theta}{\delta_e} = \frac{U_1 M_{\delta_e} (s + \frac{1}{T_{\theta_2}})}{U_1 s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)} \quad (\text{A.6})$$

Rearranging and cancelling U_1 gives

$$\frac{\theta}{\delta_e} = \frac{M_{\delta_e}}{T_{\theta_2}} \frac{(T_{\theta_2}s + 1)}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)} \quad (\text{A.7})$$

Therefore, recalling the form of Equation 2.3,

$$K_\theta = \frac{M_{\delta_e}}{T_{\theta_2}} \quad (\text{A.8})$$

Or, substituting back for $1/T_{\theta_2}$,

$$K_\theta = \frac{M_\alpha Z_{\delta_e} - M_{\delta_e} Z_\alpha}{U_1} \quad (\text{A.9})$$

The dimensional stability derivatives are defined in terms of the non-dimensional stability derivatives as follows

$$M_\alpha = \frac{\bar{q}_1 S \bar{c} C_{m_\alpha}}{I_{yy}} \quad (\text{A.10})$$

$$M_{\delta_e} = \frac{\bar{q}_1 S \bar{c} C_{m_{\delta_e}}}{I_{yy}} \quad (\text{A.11})$$

$$Z_\alpha = \frac{-\bar{q}_1 S (C_{L_\alpha} + C_{D_1})}{m} \quad (\text{A.12})$$

$$Z_{\delta_e} = \frac{-\bar{q}_1 S C_{L_{\delta_e}}}{m} \quad (\text{A.13})$$

Substituting back into Equation A.9

$$K_\theta = \frac{\bar{q}_1 S \bar{c} C_{m_{\delta_e}}}{I_{yy}} \frac{\bar{q}_1 S (C_{L_\alpha} + C_{D_1})}{m} - \frac{\bar{q}_1 S \bar{c} C_{m_\alpha}}{I_{yy}} \frac{\bar{q}_1 S C_{L_{\delta_e}}}{m} \quad (\text{A.14})$$

Or rearranging

$$K_\theta = \frac{\bar{q}_1^2 S^2 \bar{c} [C_{m_{\delta_e}} (C_{L_\alpha} + C_{D_1}) - C_{m_\alpha} C_{L_{\delta_e}}]}{I_{yy} m U_1} \quad (\text{A.15})$$

Appendix B. Neal-Smith Test Data

Table B.1 is data from Reference [3, 13] with the parameters the Ralph Smith criteria uses.

Table B.1: Neal-Smith Test Data

<i>Case</i>	t_q	\bar{S}	ω_c	$\angle_{\frac{\theta}{F_s}}(j\omega_c)$	<i>Average Cooper-Harper Rating</i>
1A	.56	-9	3.8	-136	5
1B	.58	-8	4.1	-132	3.25
1C	.65	-8.5	4	-148	4.5
1D	1.0	-11	3.2	-148	4.125
1E	1.35	-13	2.7	-162	6
1F	1.85	-15	2.2	-180	8
1G	1.5	-15	2.2	-204	8.5
2A	.26	-1	6	-97	4.25
2B	.35	-2	6	-130	5.125
2C	.24	-3	5.5	-89	3
2D	.3	-4	5.2	-107	2.66
2E	.45	-4	5.2	131	4
2F	.6	-6	4.6	-143	3
2G	.6	-6	4.6	-168	7
2H	.7	-8	4.1	-157	5.5
2I	.85	-8	4.1	-179	8
2J	3	-9	3.8	-171	6
3A	.15	-1	6	-63	4.25
3B	.25	-1	6	-90	4.5
3C	.3	-3	5.5	-107	3.5
3D	.35	-5	4.9	-123	4
3E	3.5	-6	4.6	-137	4
4A	.3	2	6	-135	5.25
4B	.45	2	6	-162	7
4C	.57	-2	5.7	-175	8
4D	.65	-5	4.9	-168	8
4E	.7	-6	4.60	-173	7
5A	.3	5.5	6	-144	6

<i>Case</i>	t_q	\bar{S}	ω_c	$\angle \frac{\theta}{F_s}(j\omega_c)$	<i>Average Cooper-Harper Rating</i>
5B	.43	4.5	6	-171	7
5C	.44	2	6	-194	8
5D	.7	-1	6	-221	8
5E	.7	-1	6	-234	8
6A	.53	-1	6	-132	5.5
6B	.48	-6	4.6	-118	2.5
6C	.7	-8	4.1	-136	3.83
6D	.95	-8	4.1	-162	5.5
6E	1.25	-11	3.3	-168	7.75
6F	2.8	-13	2.7	-186	8.83
7A	.2	-1	6	-72	3.66
7B	.18	-2	5	-75	3
7C	.2	-3	5.5	-92	2.875
7D	.3	-4	5.2	-104	5.5
7E	.45	-5	4.9	-119	3
7F	.63	-5	4.9	-143	7
7G	.73	-7	4.4	-149	5.5
7H	2.5	-9	3.8	-157	5
8A	.1	-2	5.7	-51	4.5
8B	.2	-2	5.7	-68	3.5
8C	.21	-3	5.5	-86	3.25
8D	.28	-5	4.9	-107	3
8E	2.17	-8	4.1	-129	3.5
9	2.4	-8	4.1	-127	5.5
10	.95	-8	4.1	-134	4
11	.6	-7	4.4	-121	2.75
12	.15	-1	6	-62	5.66
13	.15	-1	6	-44	6.25
14	.1	-1	6	-34	5.25

Appendix C. Test Cases and Results

This appendix includes all the cases tested in this research study. Table C.1 shows all of the cases studied.

Table C.1: Test Cases Examined

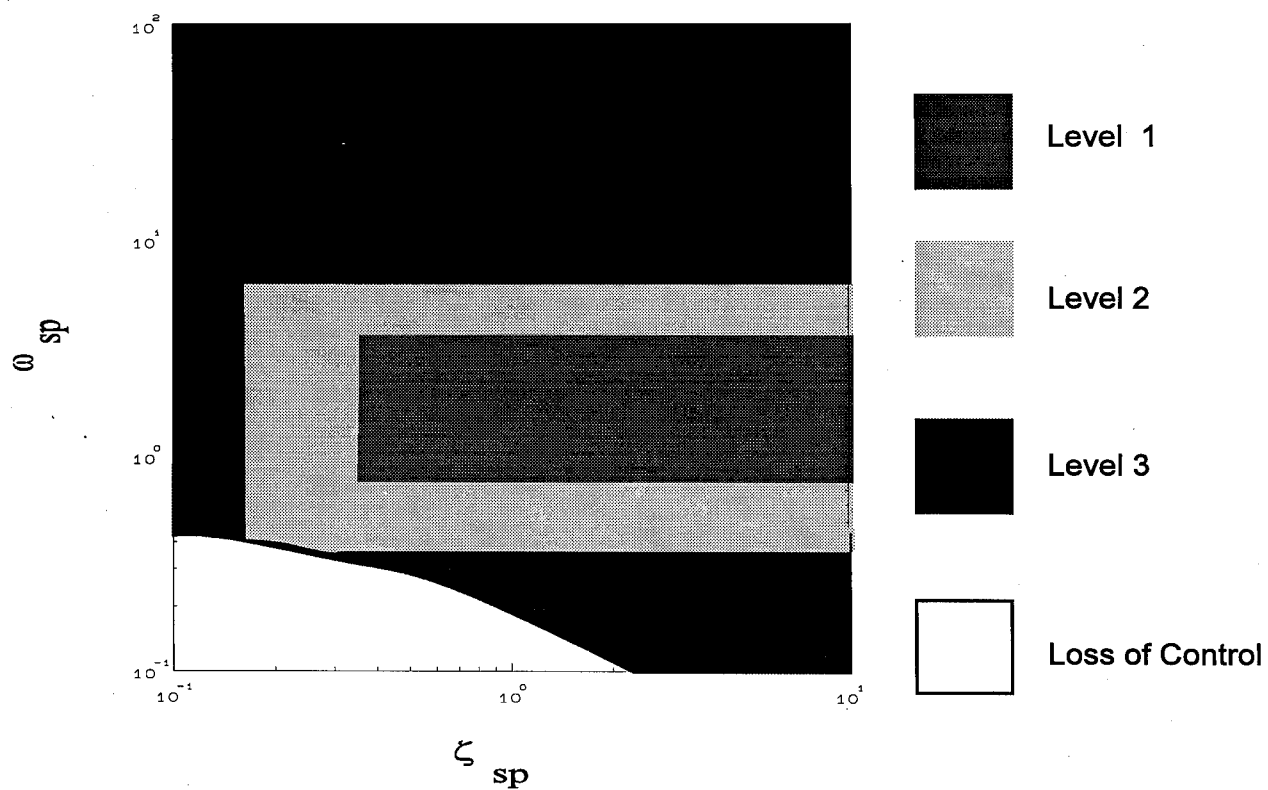
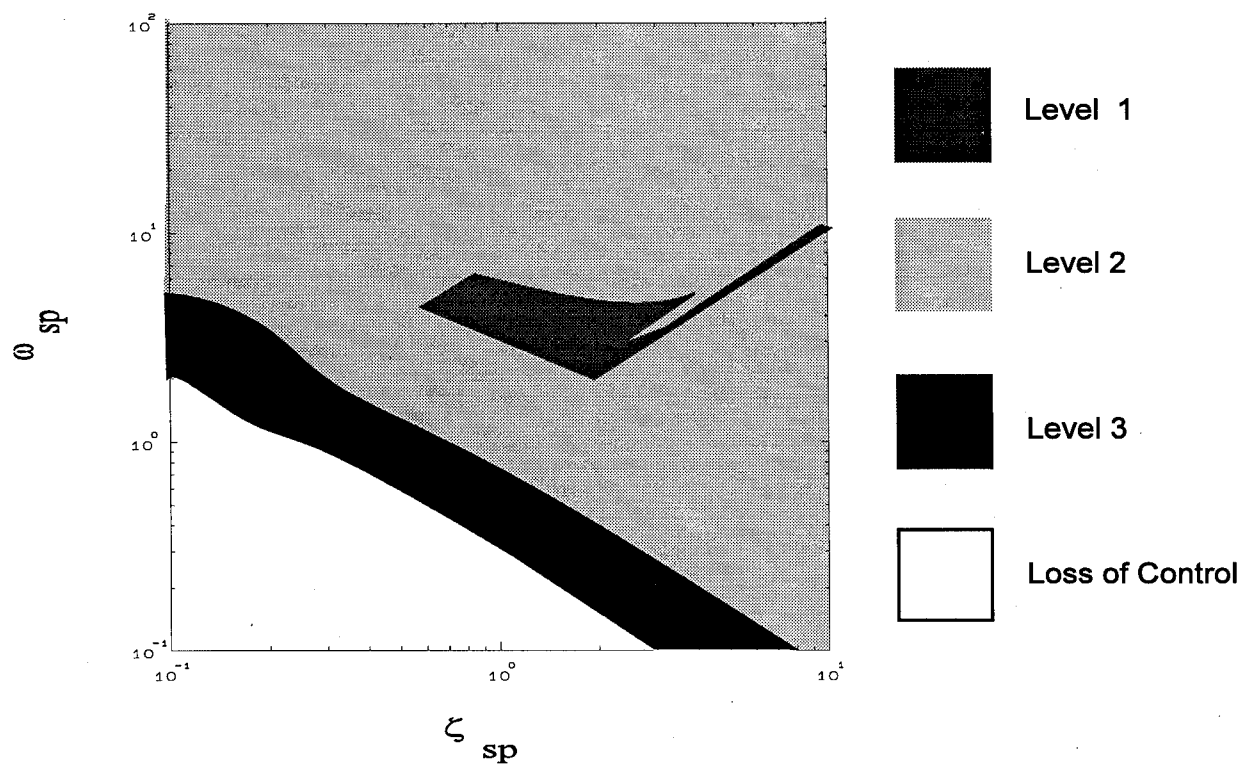
<i>Case</i>	<i>Height</i>	<i>Velocity</i>	T_{θ_2}	K_{θ}	τ_{θ}	<i>Remarks</i>
	<i>m (ft)</i>	<i>m/s (ft/s)</i>			<i>s</i>	
1	304.8 (1000)	65.23 (214)	1.17	2.44	0	Learjet Transfer Function I
2					.1	
3					.15	
4					.2	
5	0	65.23 (214)	1.41	3.08	0	Learjet Transfer Function II
6					.1	
7					.15	
8					.2	
9	0	51.82 (170)	1.32	3.9897	0	Learjet Transfer Function III
10					.1	
11					.15	
12					.2	
13	1524 (5000)	77.11 (253)	2.12	.237	0	F-16 Transfer Function I
14					.1	
15					.15	
16					.2	
17	304.8 (1000)	65.23 (214)	1.69	.1144	0	F-16 Transfer Function II
18					.1	
19					.15	
20					.2	
21	30.48 (100)	64.2 (212)	1.77	.1431	0	F-16 Transfer Function III
22					.1	
23					.15	
24					.2	

Each case represents a unique flight condition. The data given in Table C.1 contains all the pertinent information required to create the numerator of the transfer function. All cases are presented with six figures, in a similar manner to the example of Chapter III.

C.1 Case 1

Lear Jet Transfer Function I

$$\frac{\theta(s)}{\delta(s)} = \frac{2.44(1.17s + 1)e^{0s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$



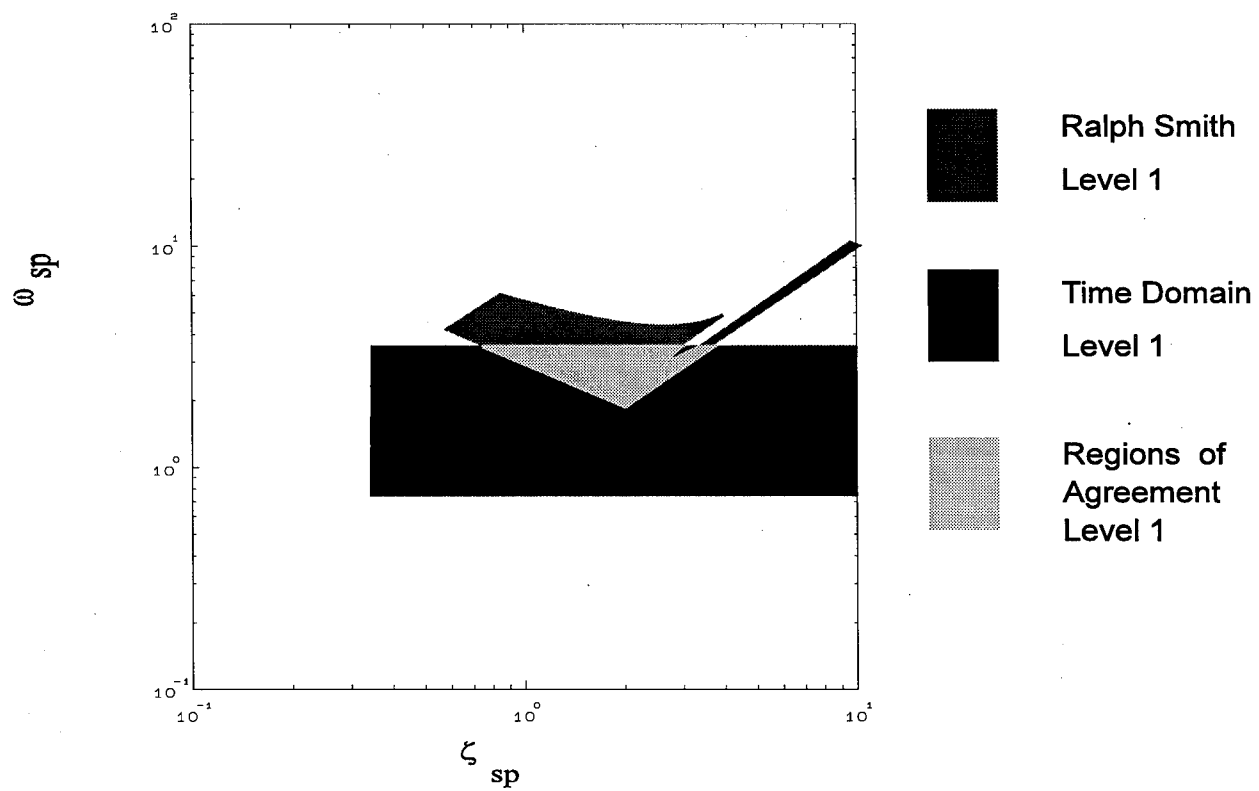


Figure C.3: Level 1 Regions (Case 1)

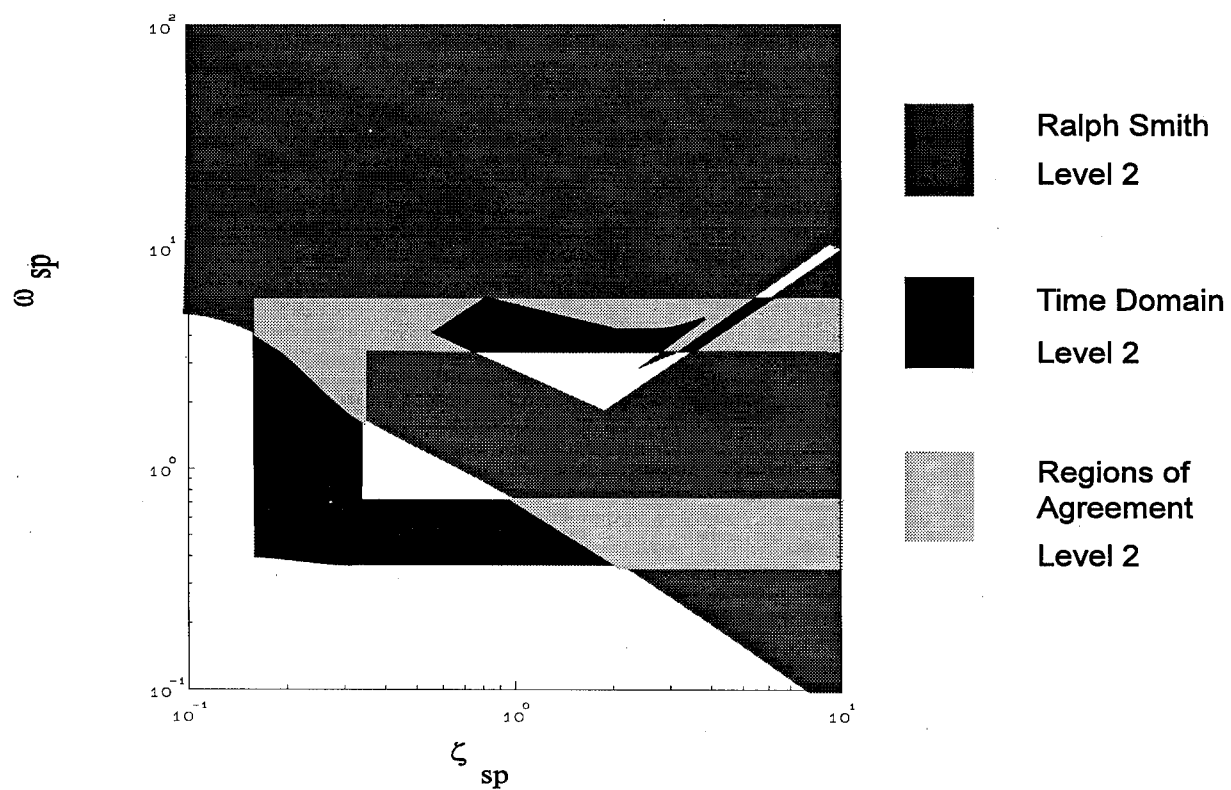


Figure C.4: Level 2 Regions (Case 1)

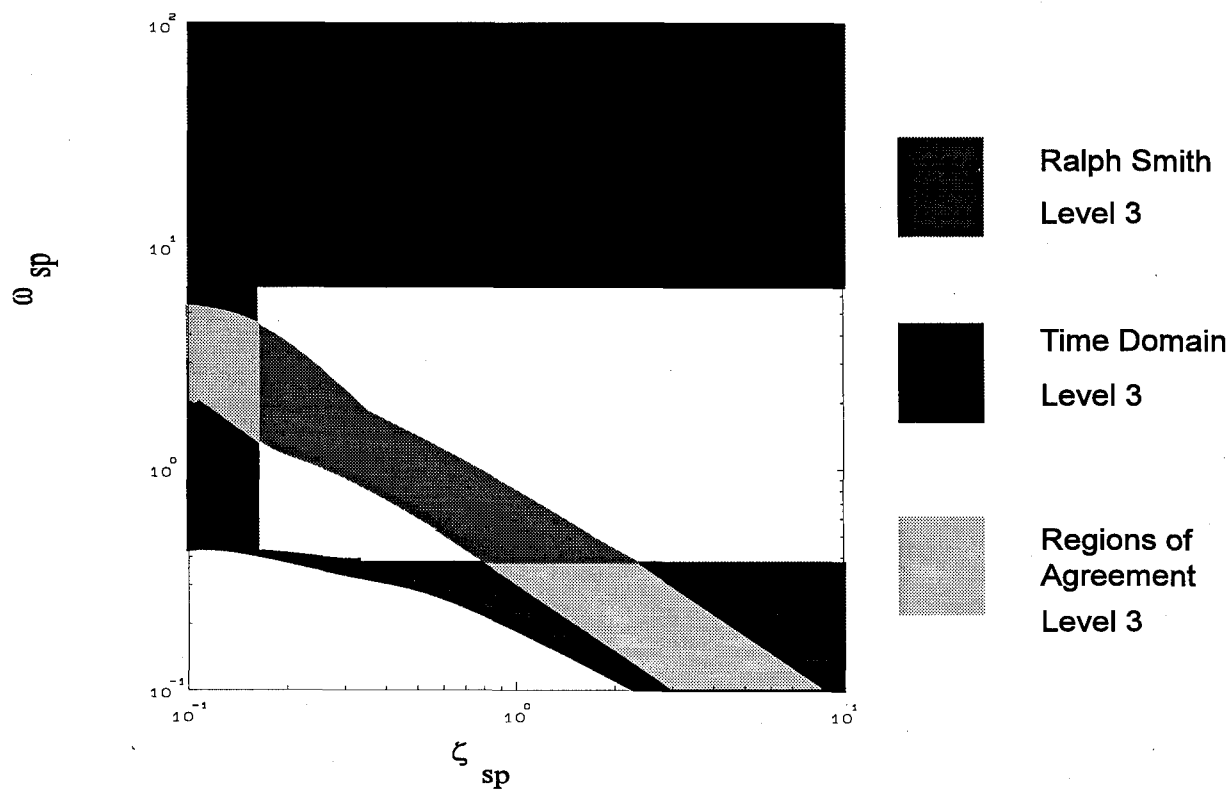


Figure C.5: Level 3 Regions (Case 1)

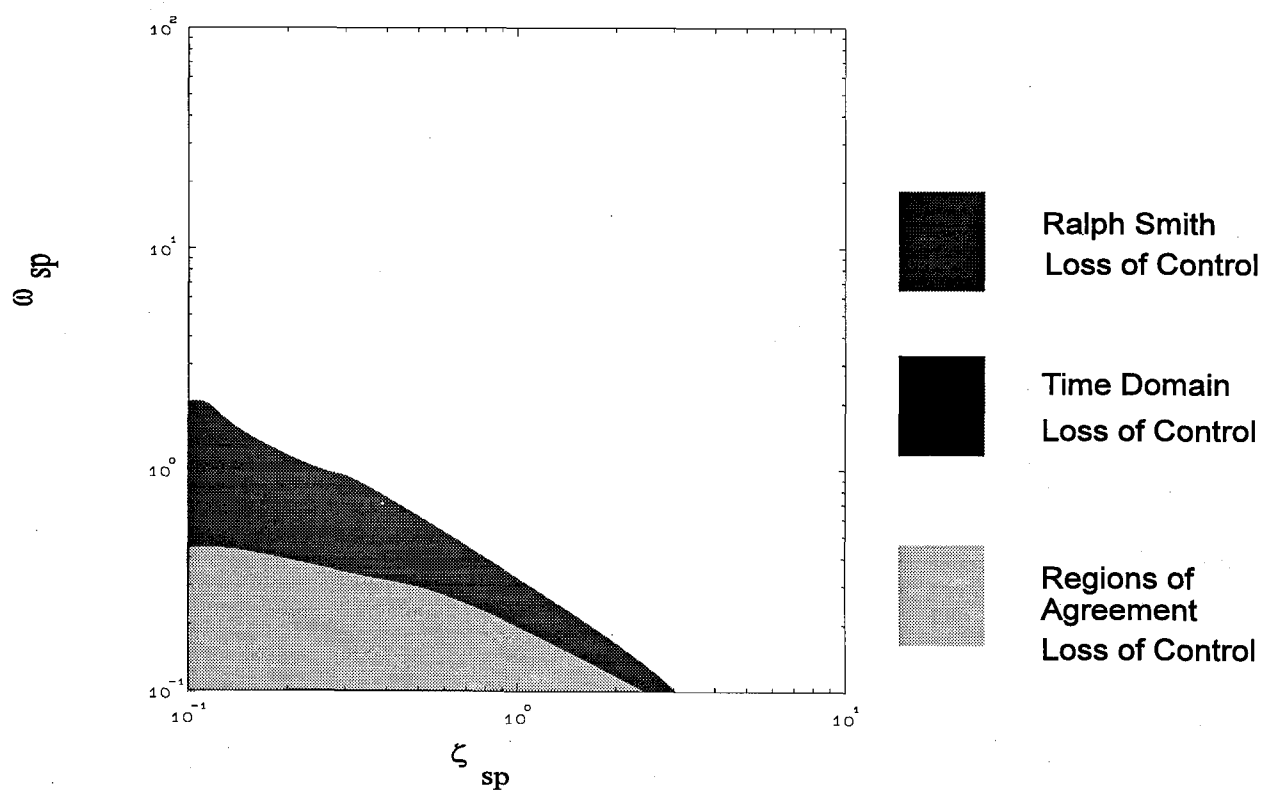


Figure C.6: Loss of Control Regions (Case 1)

C.2 Case 2

$$\frac{\theta(s)}{\delta(s)} = \frac{2.44(1.17s + 1)e^{-.1s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

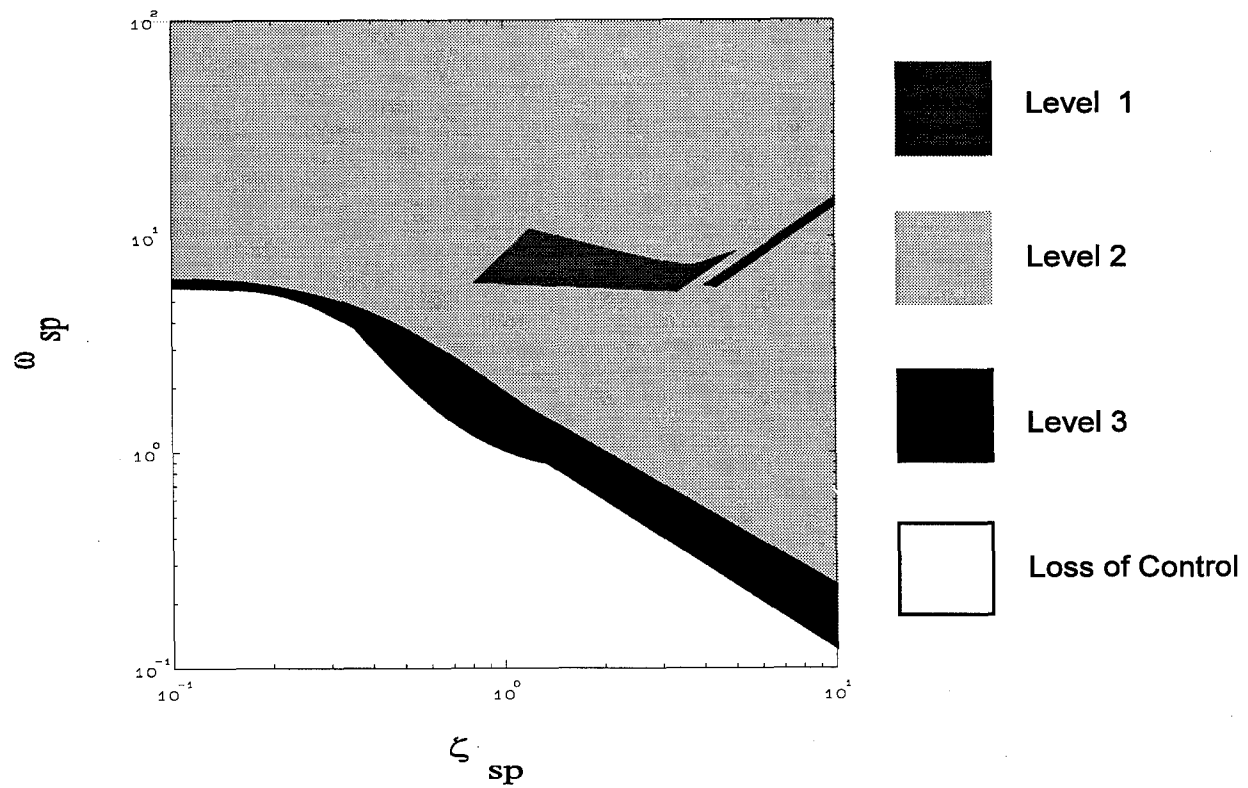


Figure C.7: Ralph Smith Criteria (Case 2)

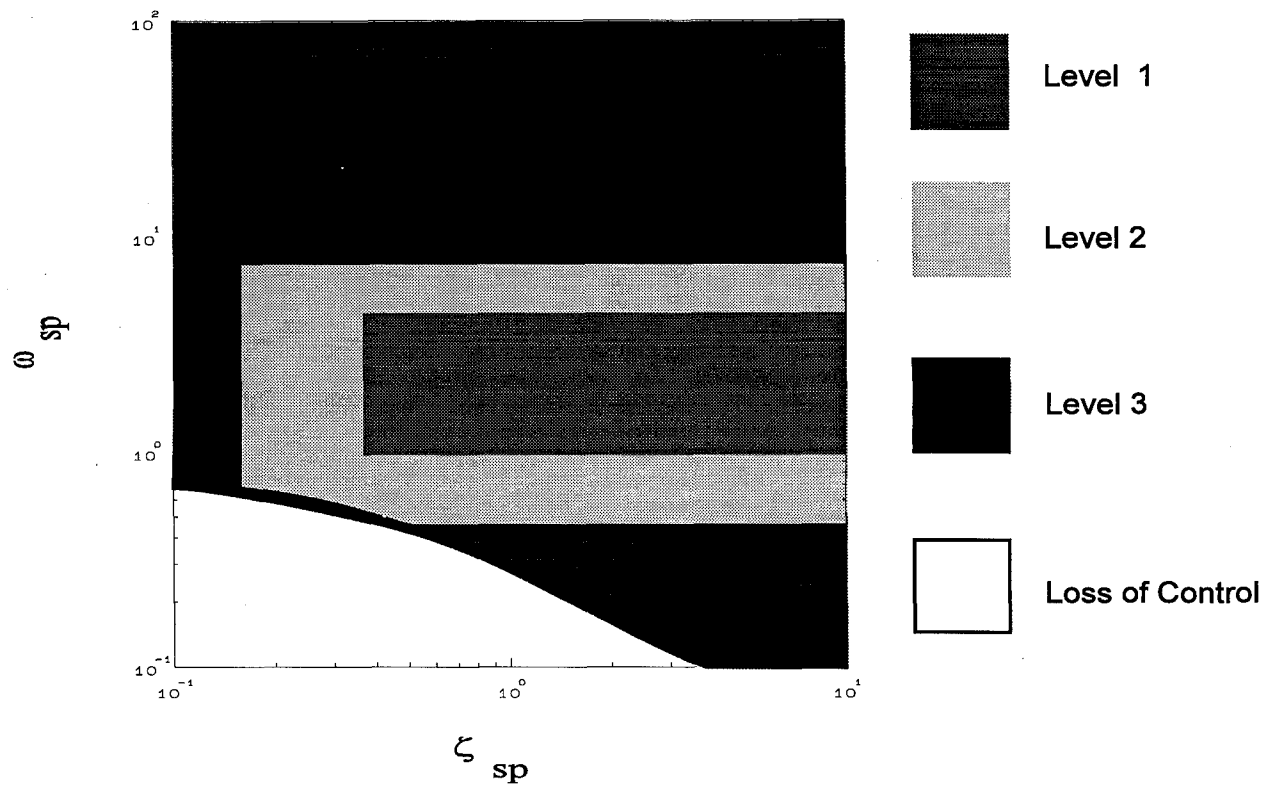
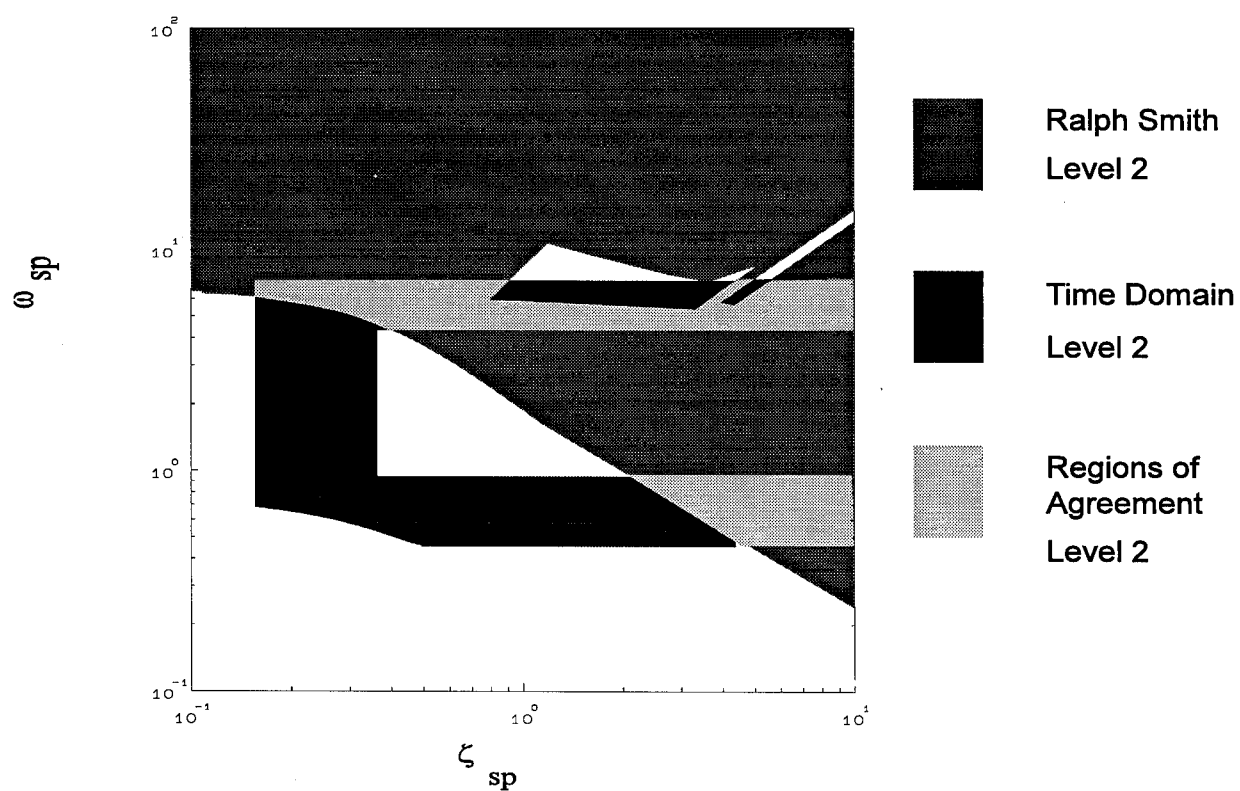
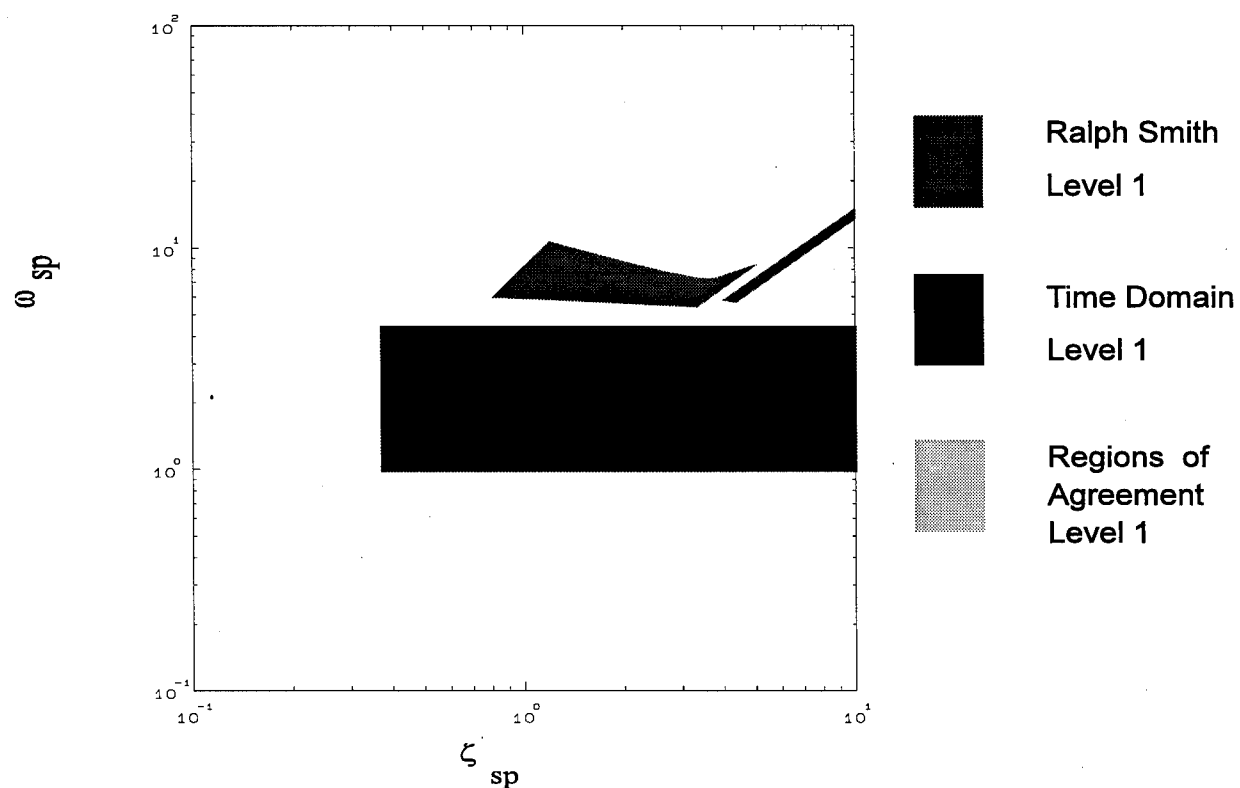


Figure C.8: Time Domain Criteria (Case 2)



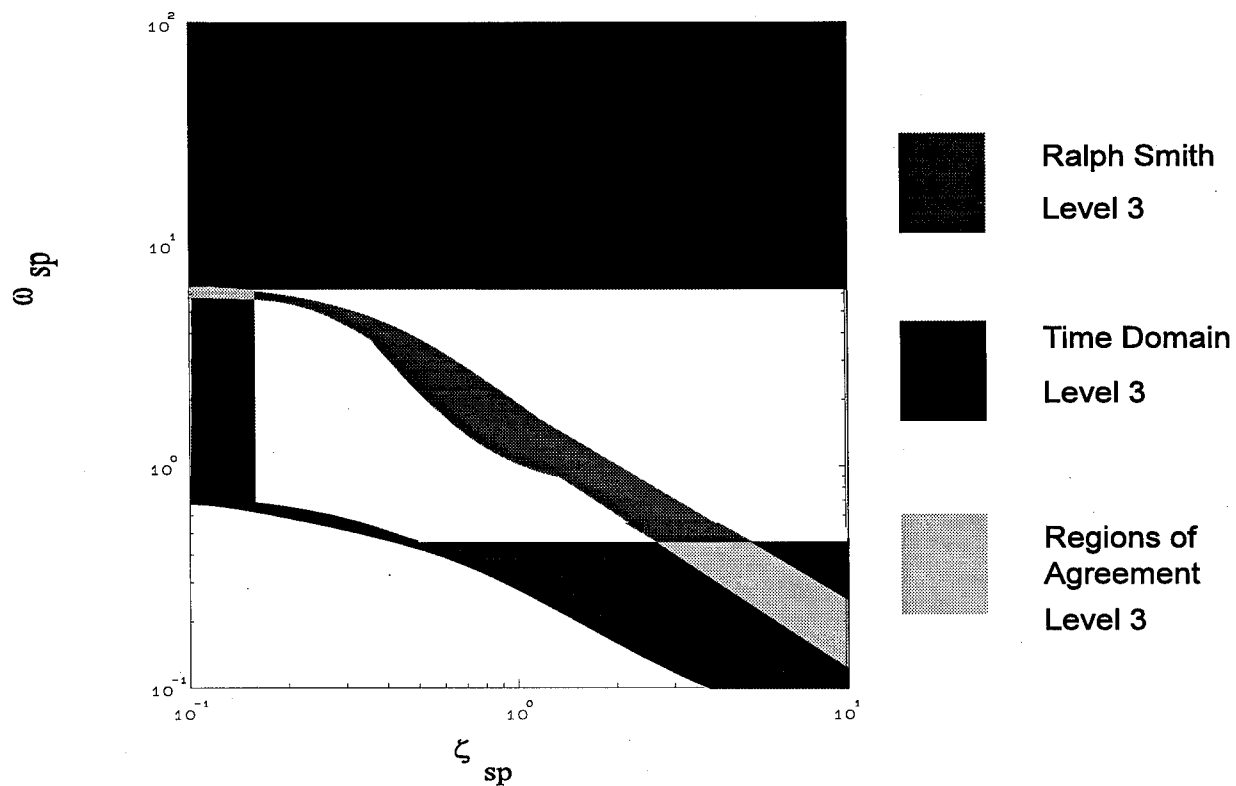


Figure C.11: Level 3 Regions (Case 2)

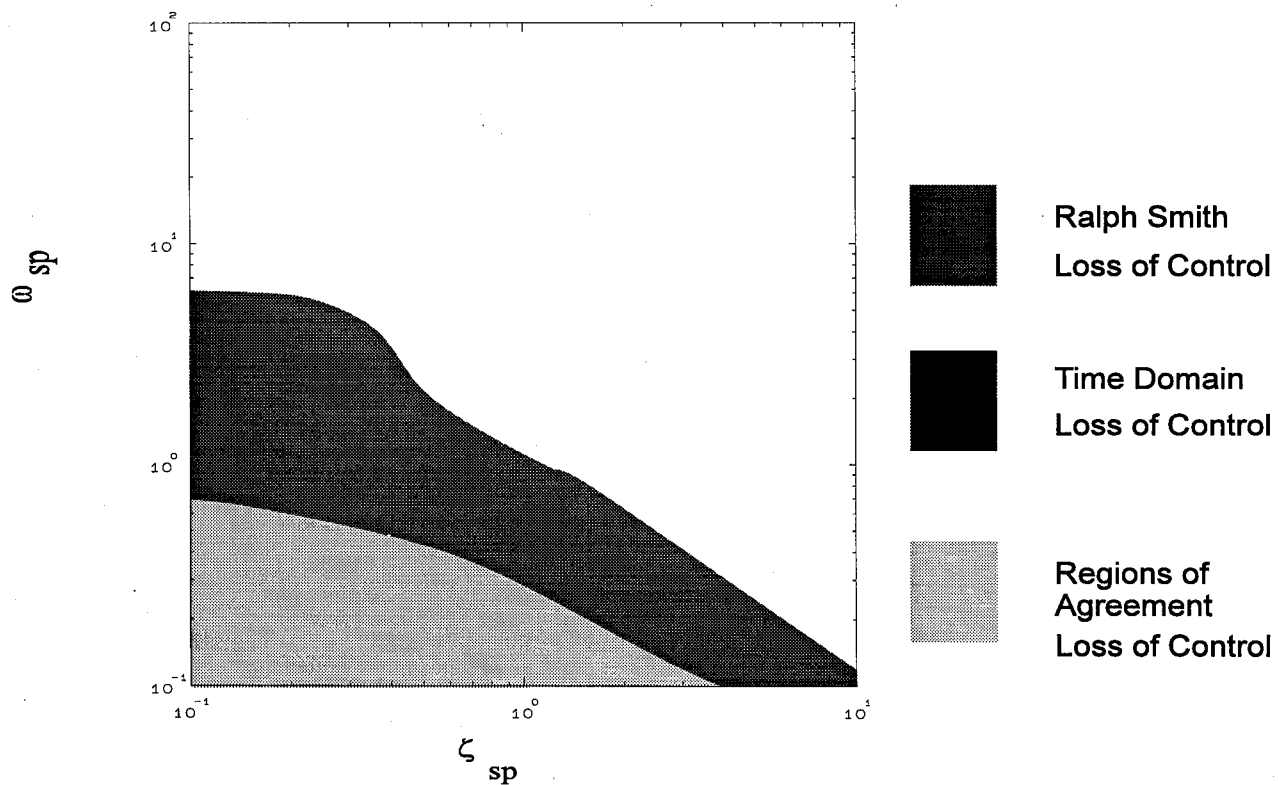


Figure C.12: Loss of Control Regions (Case 2)

C.3 Case 3

$$\frac{\theta(s)}{\delta(s)} = \frac{2.44(1.17s + 1)e^{-.15s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

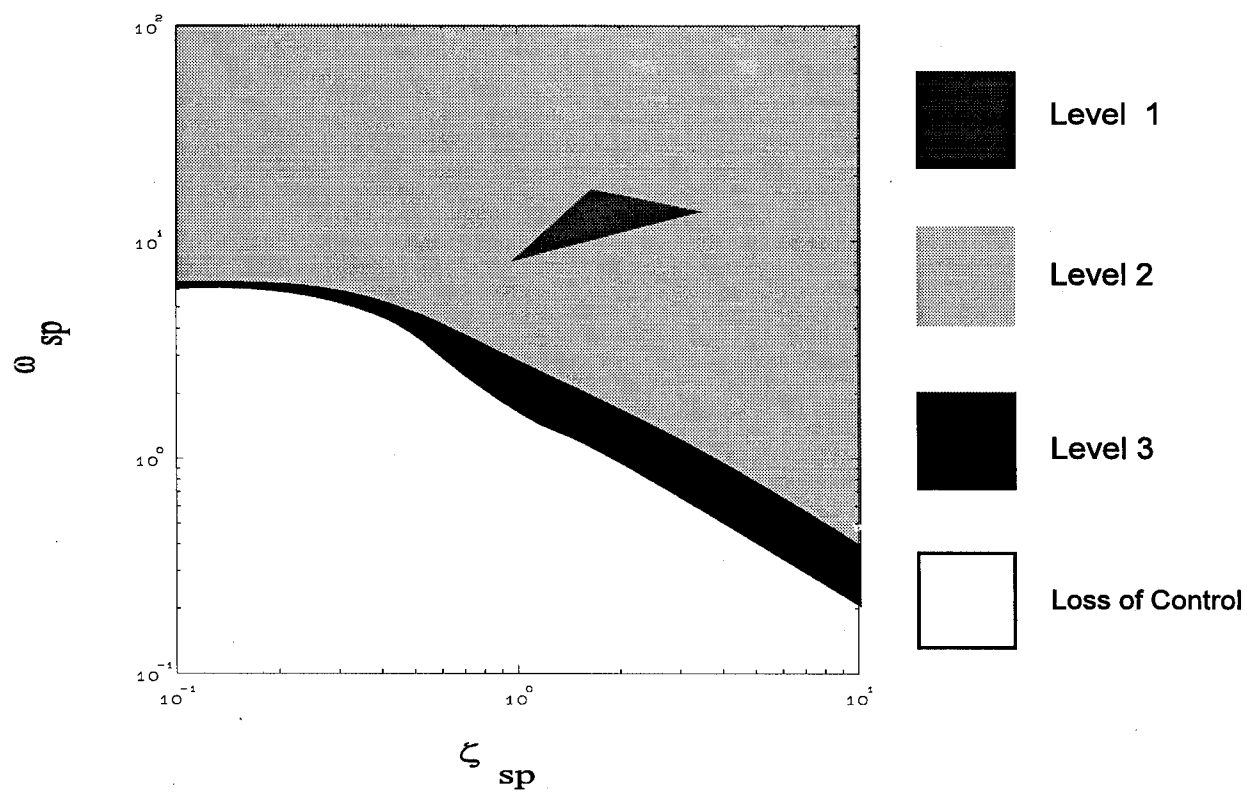


Figure C.13: Ralph Smith Criteria (Case 3)

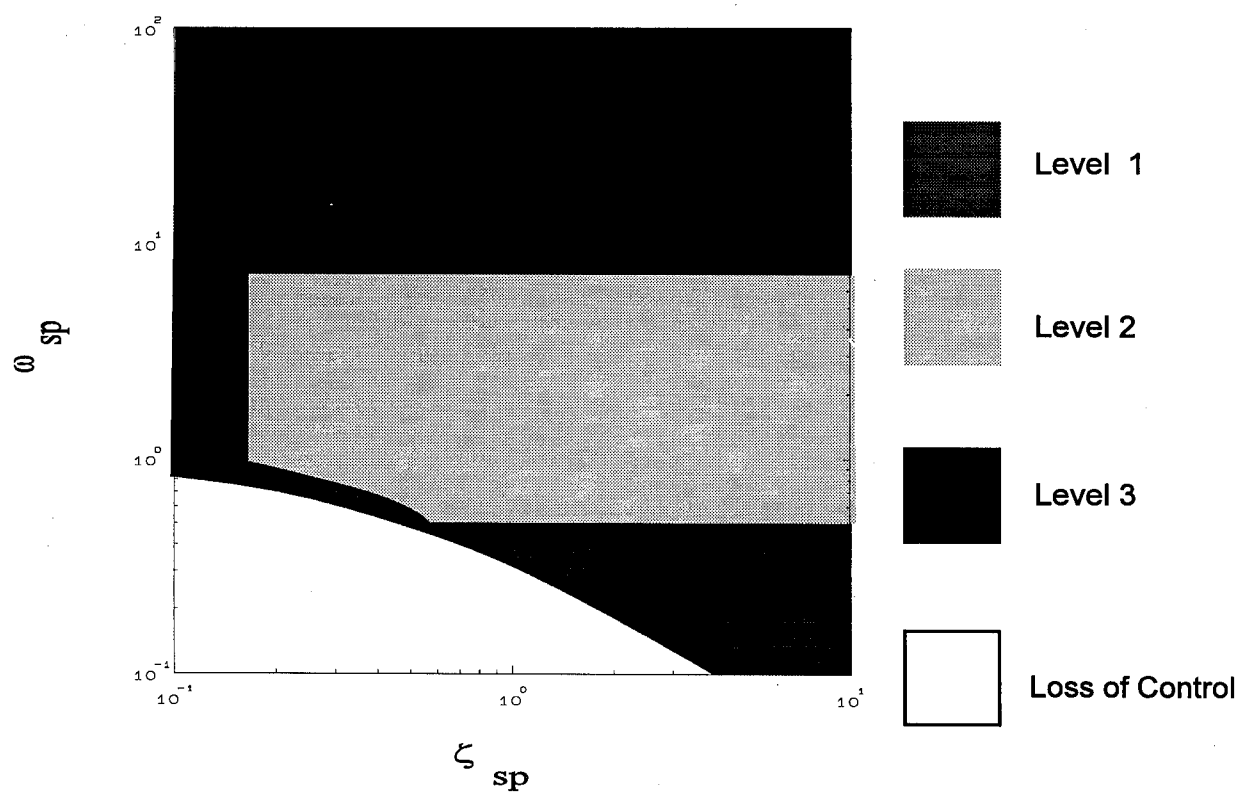


Figure C.14: Time Domain Criteria (Case 3)

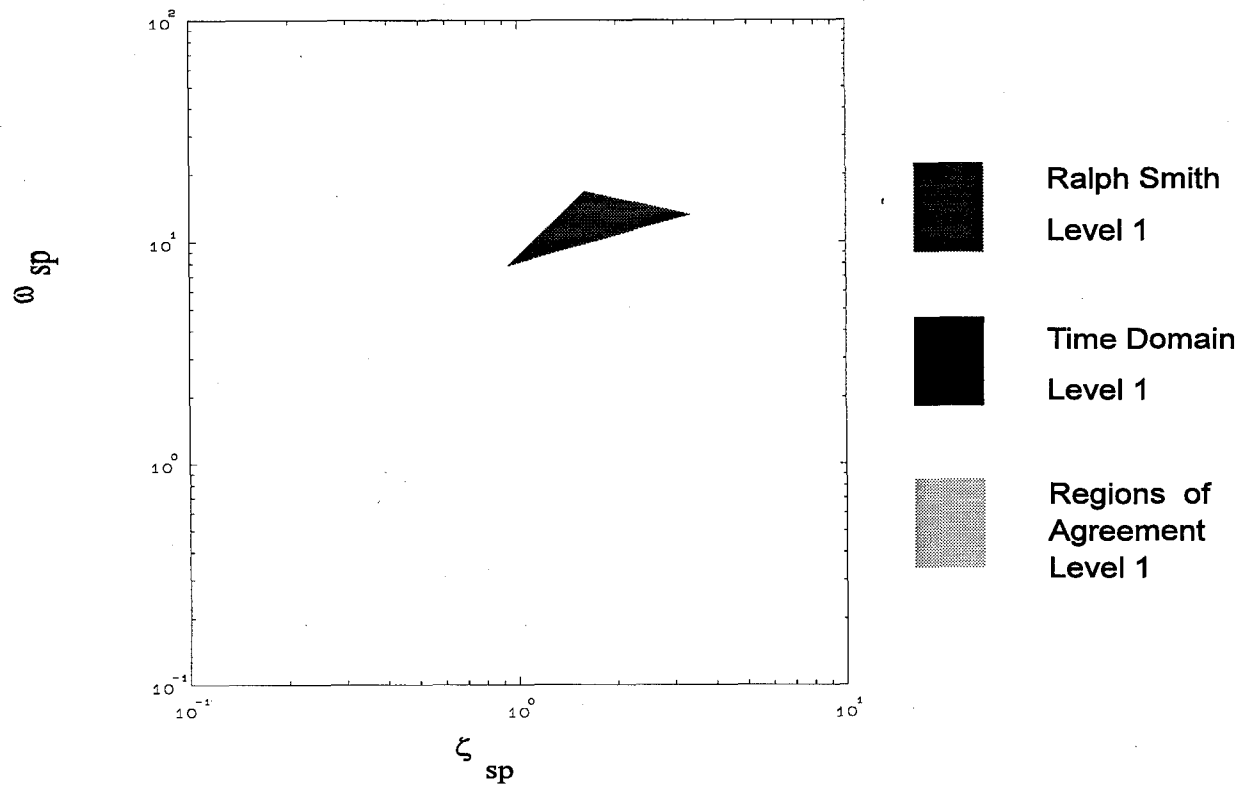


Figure C.15: Level 1 Regions (Case 3)

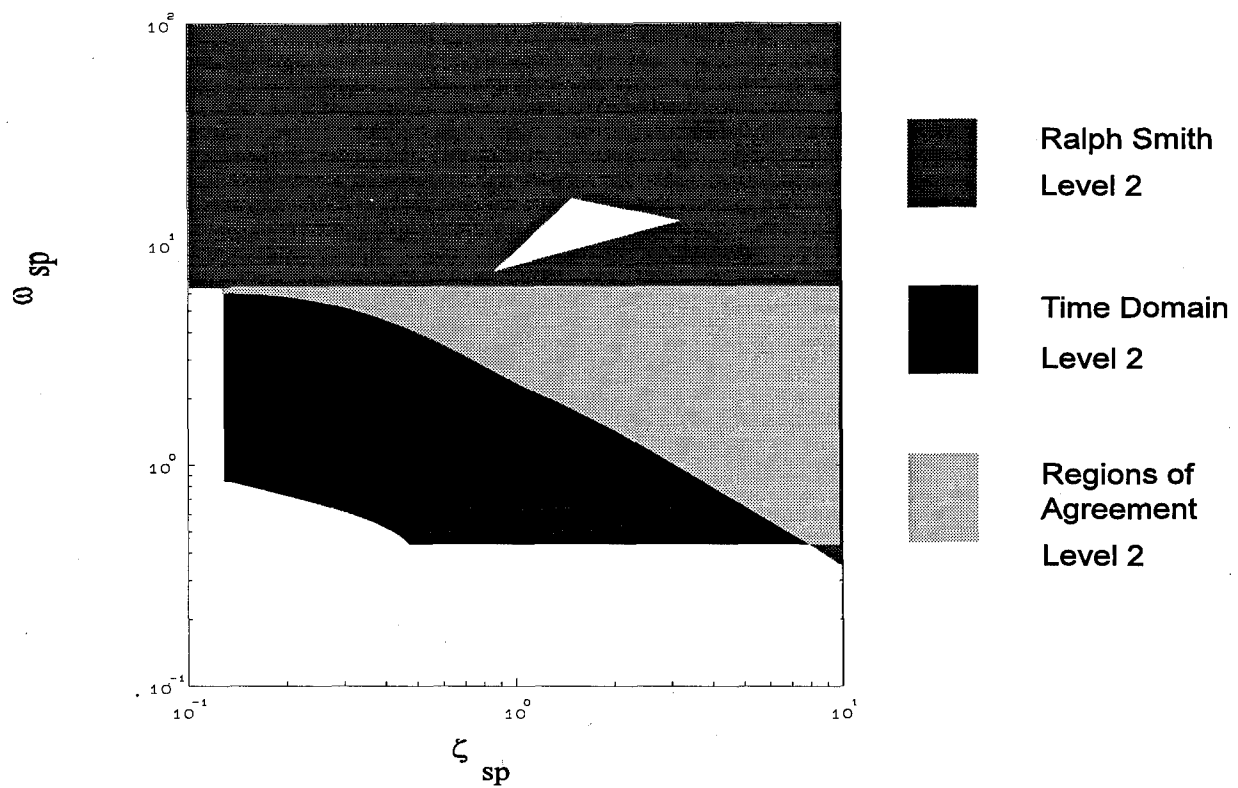


Figure C.16: Level 2 Regions (Case 3)

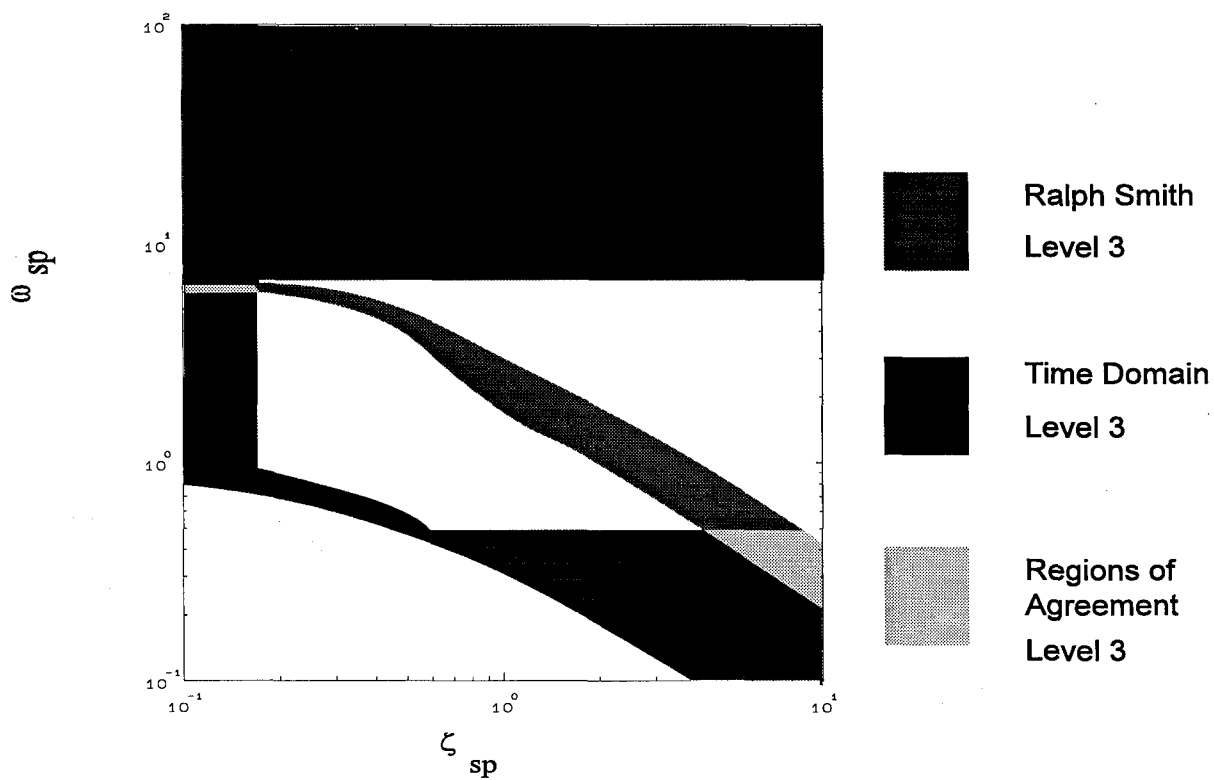


Figure C.17: Level 3 Regions (Case 3)

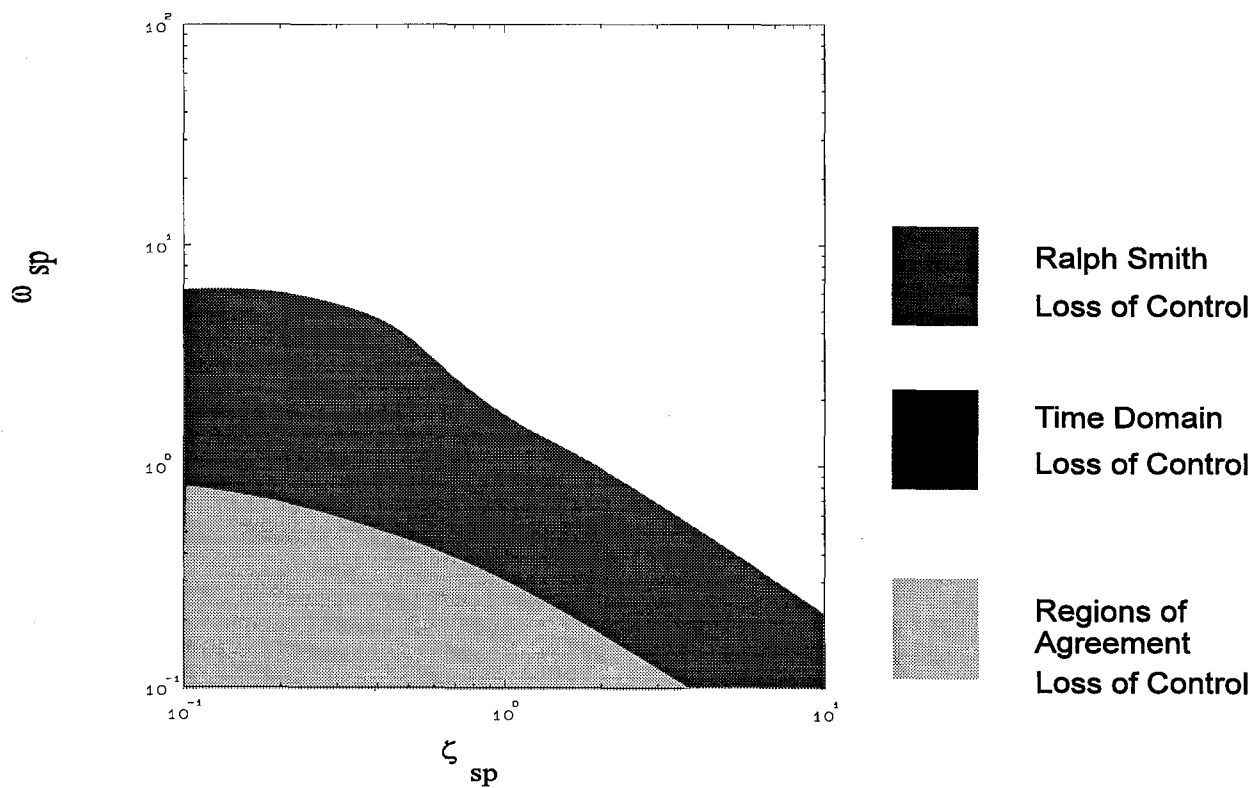
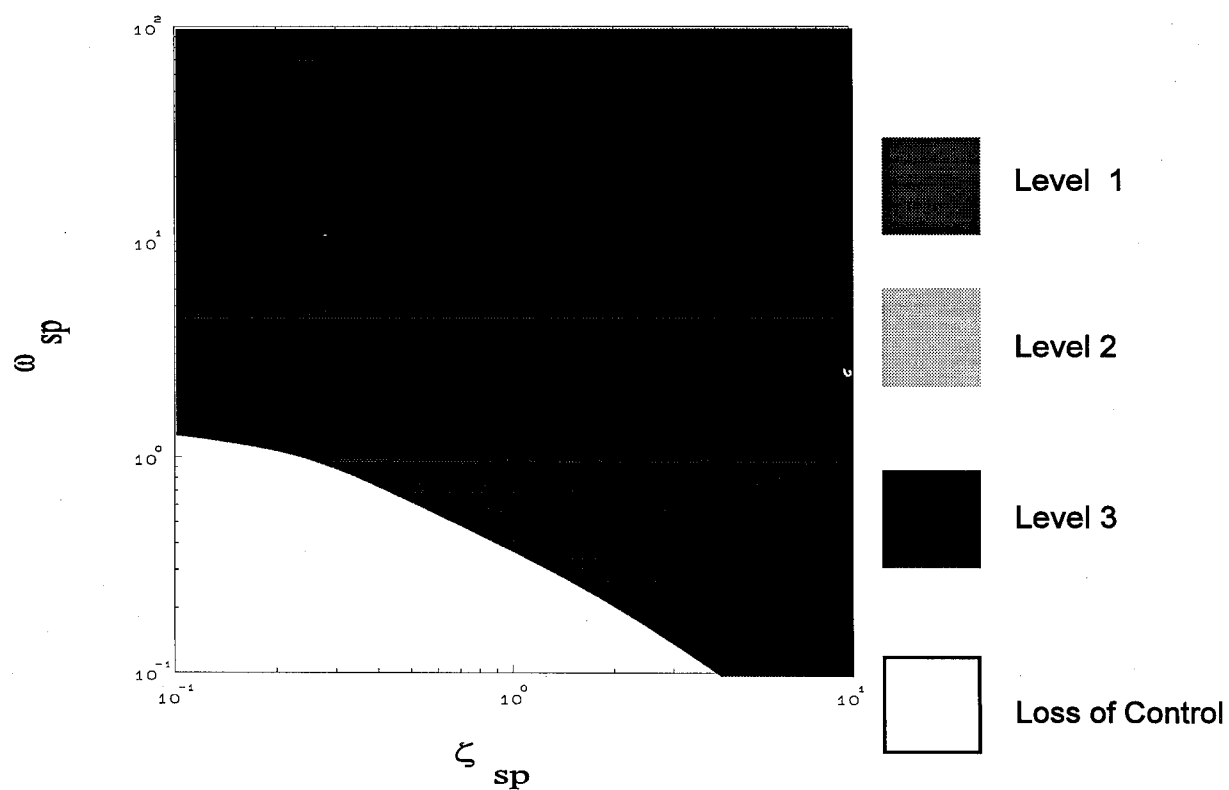
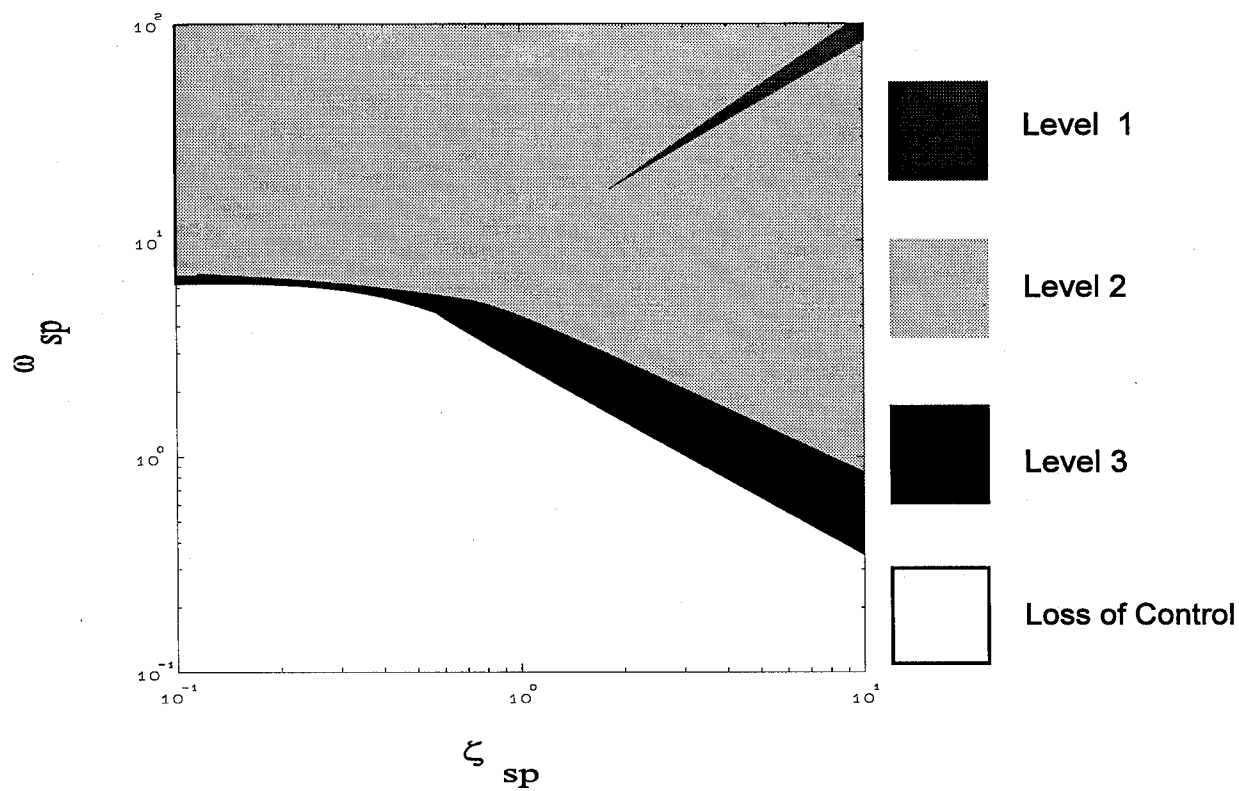


Figure C.18: Loss of Control Regions (Case 3)

C.4 Case 4

$$\frac{\theta(s)}{\delta(s)} = \frac{2.44(1.17s + 1)e^{-.2s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$



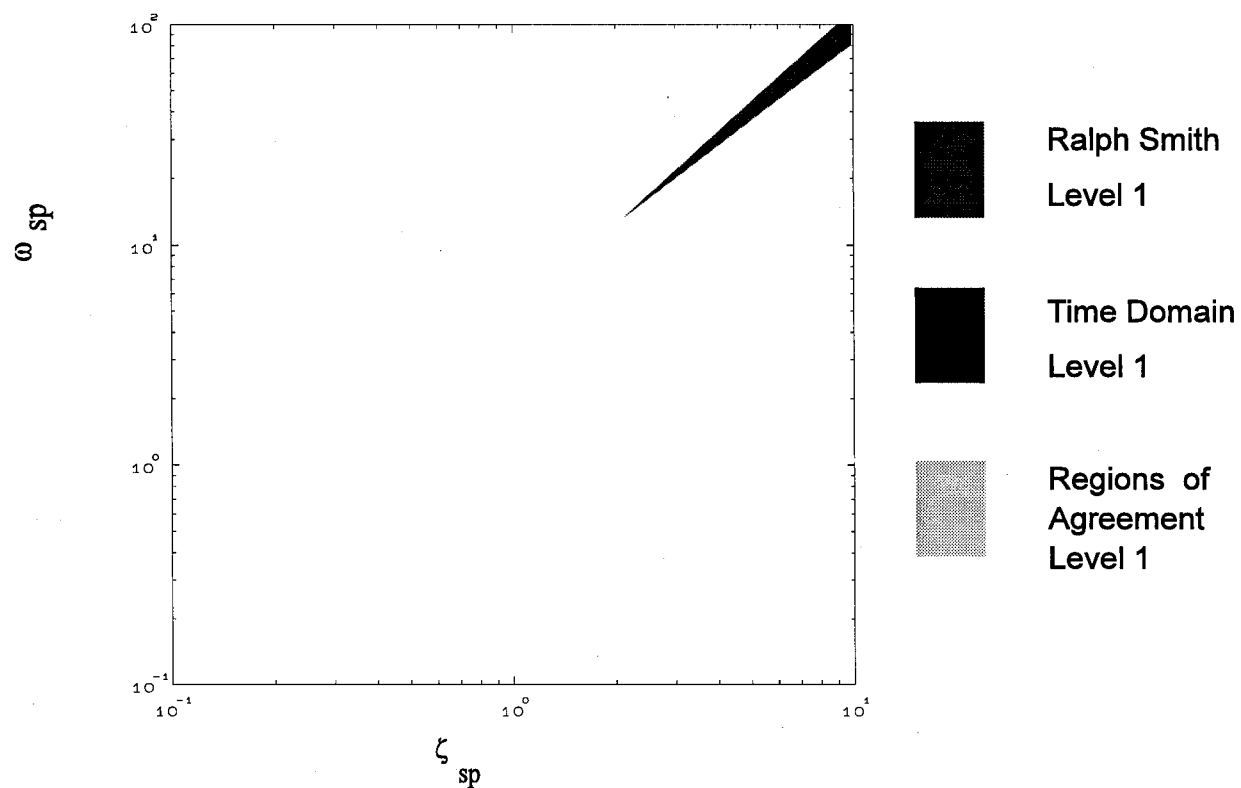


Figure C.21: Level 1 Regions (Case 4)

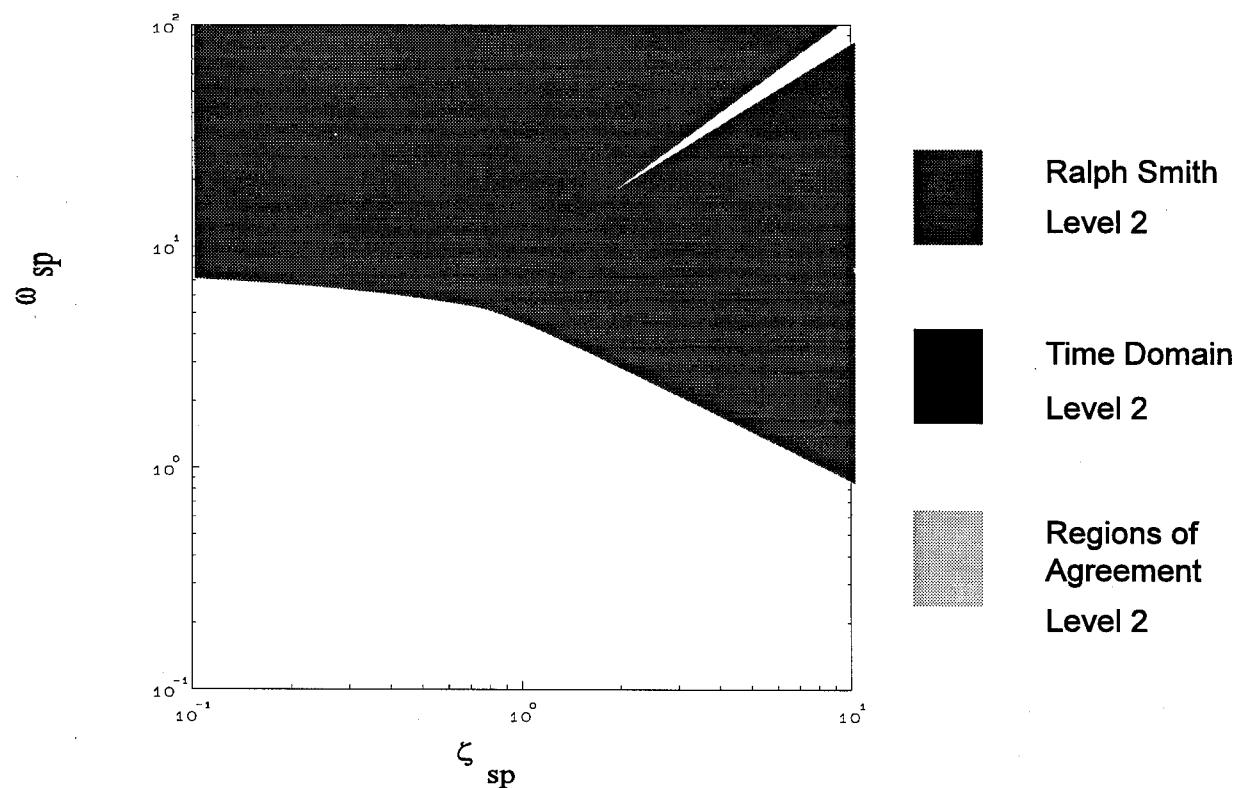


Figure C.22: Level 2 Regions (Case 4)

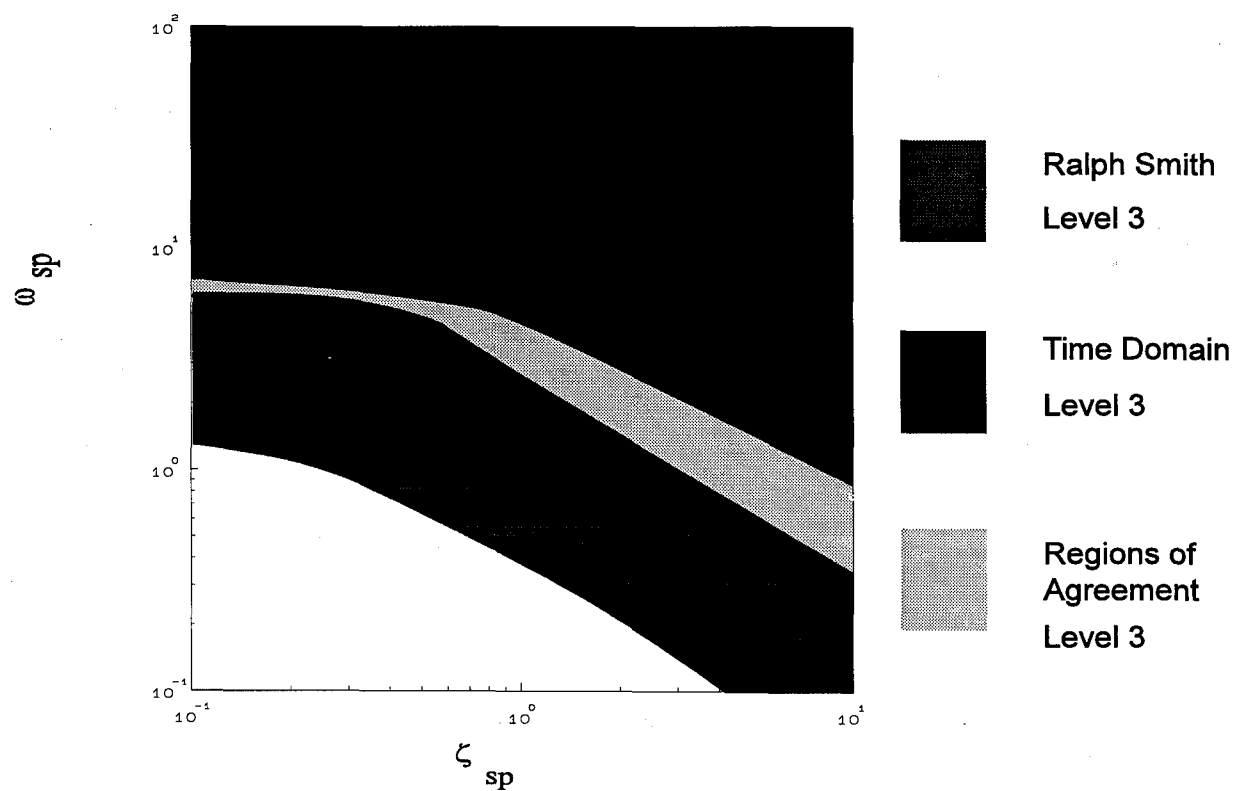


Figure C.23: Level 3 Regions (Case 4)

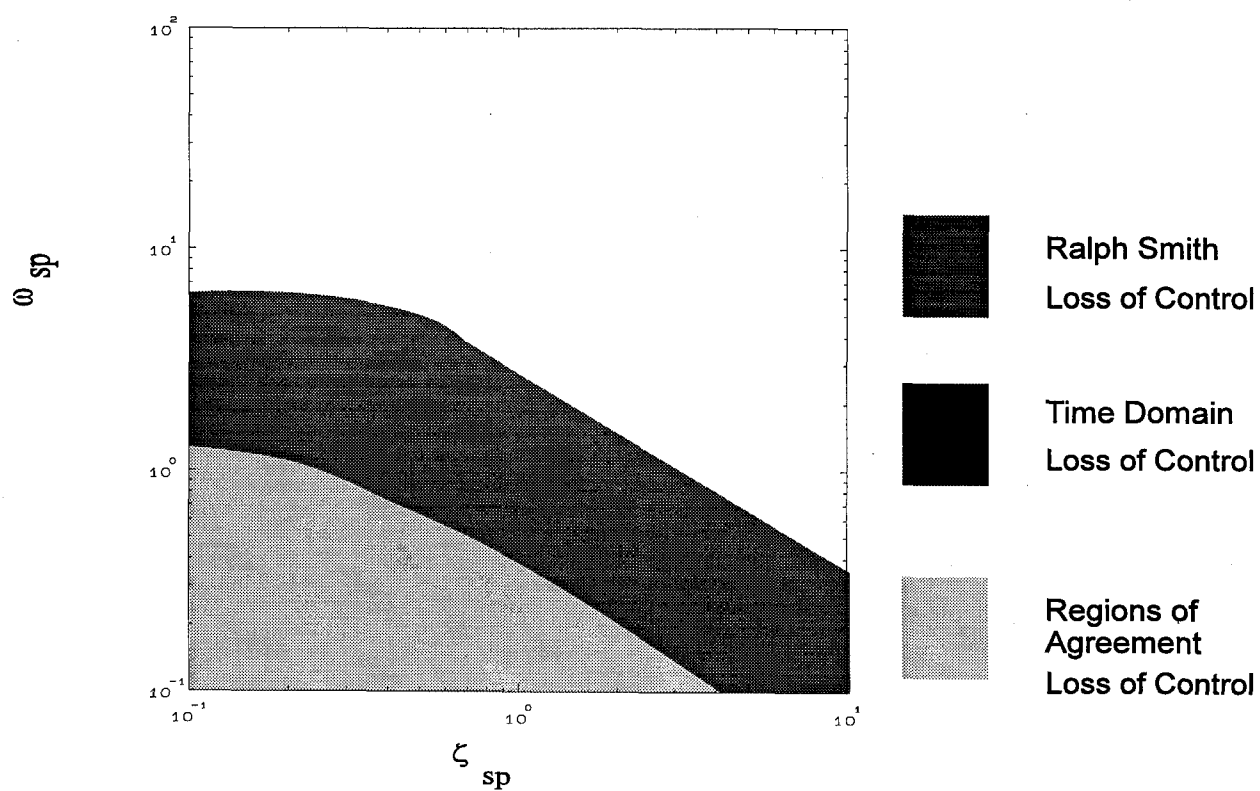


Figure C.24: Loss of Control Regions (Case 4)

C.5 Case 5

Lear Jet Transfer Function II

$$\frac{\theta(s)}{\delta(s)} = \frac{3.08(1.41s + 1)e^{0s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

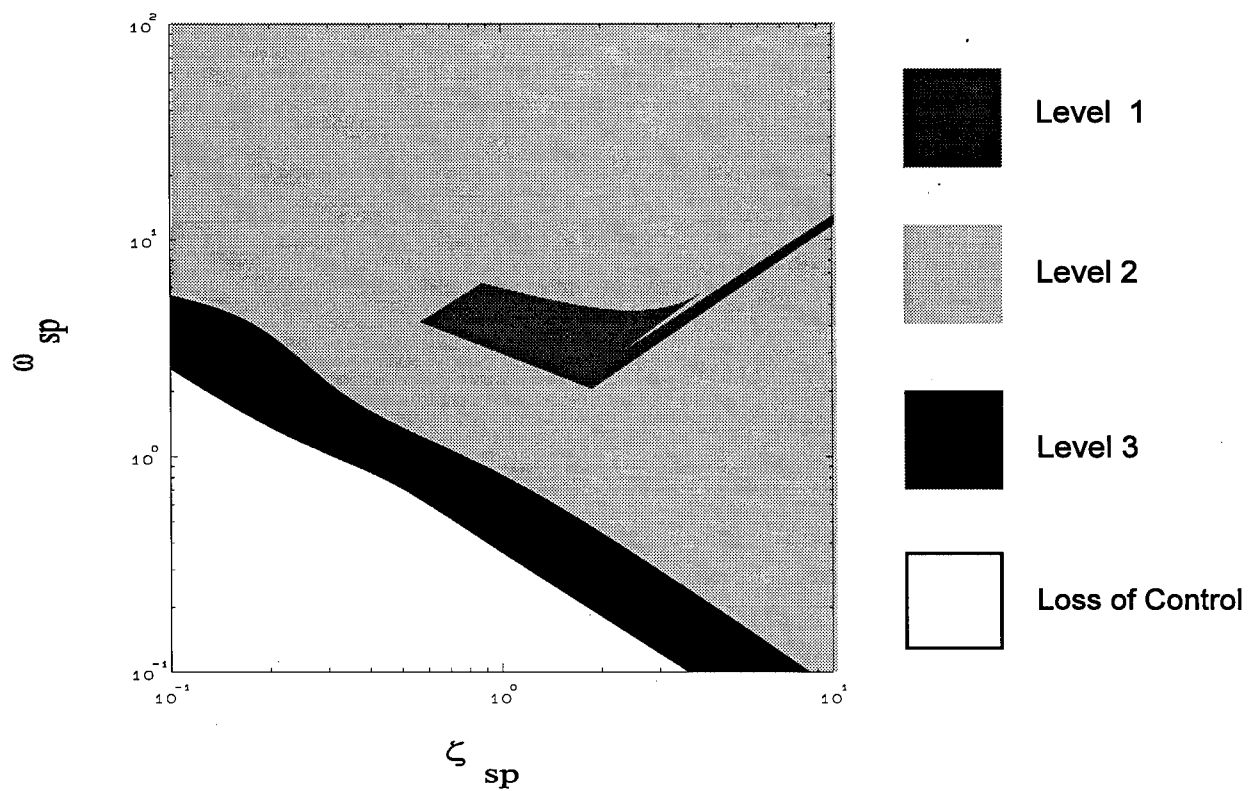


Figure C.25: Ralph Smith Criteria (Case 5)

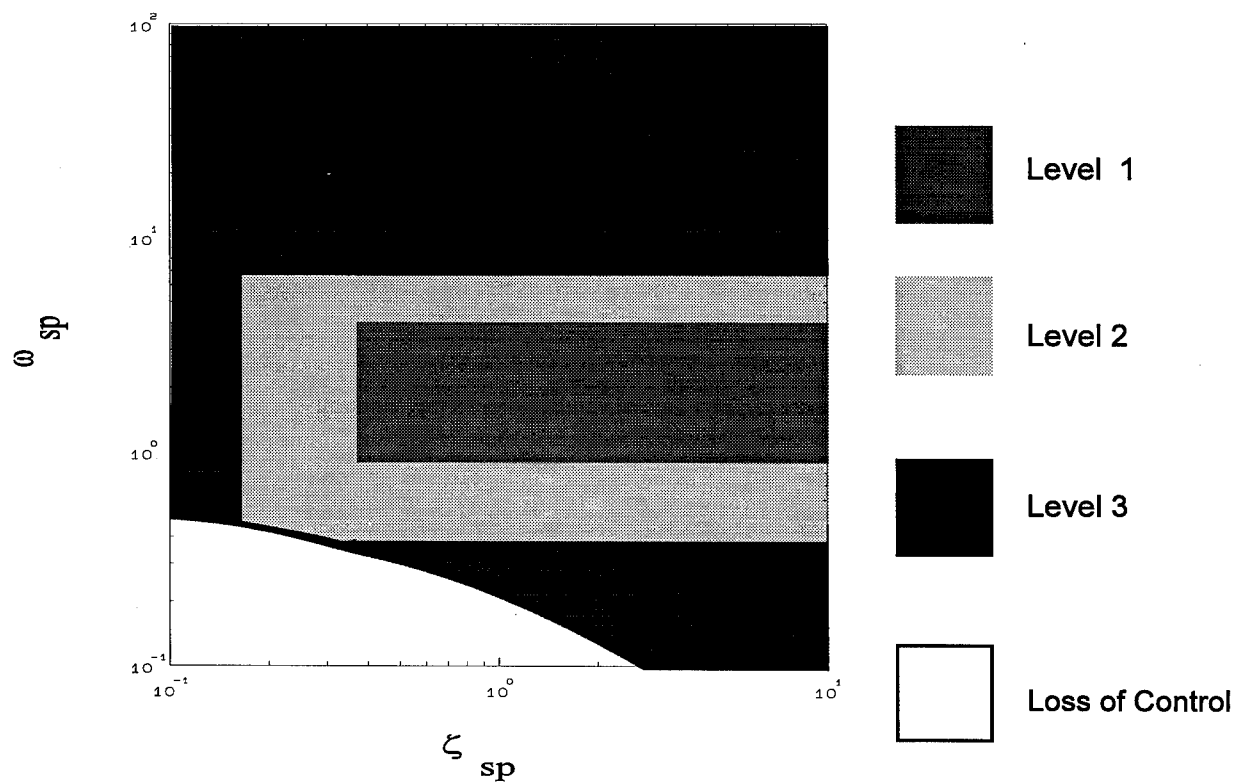


Figure C.26: Time Domain Criteria Case 5

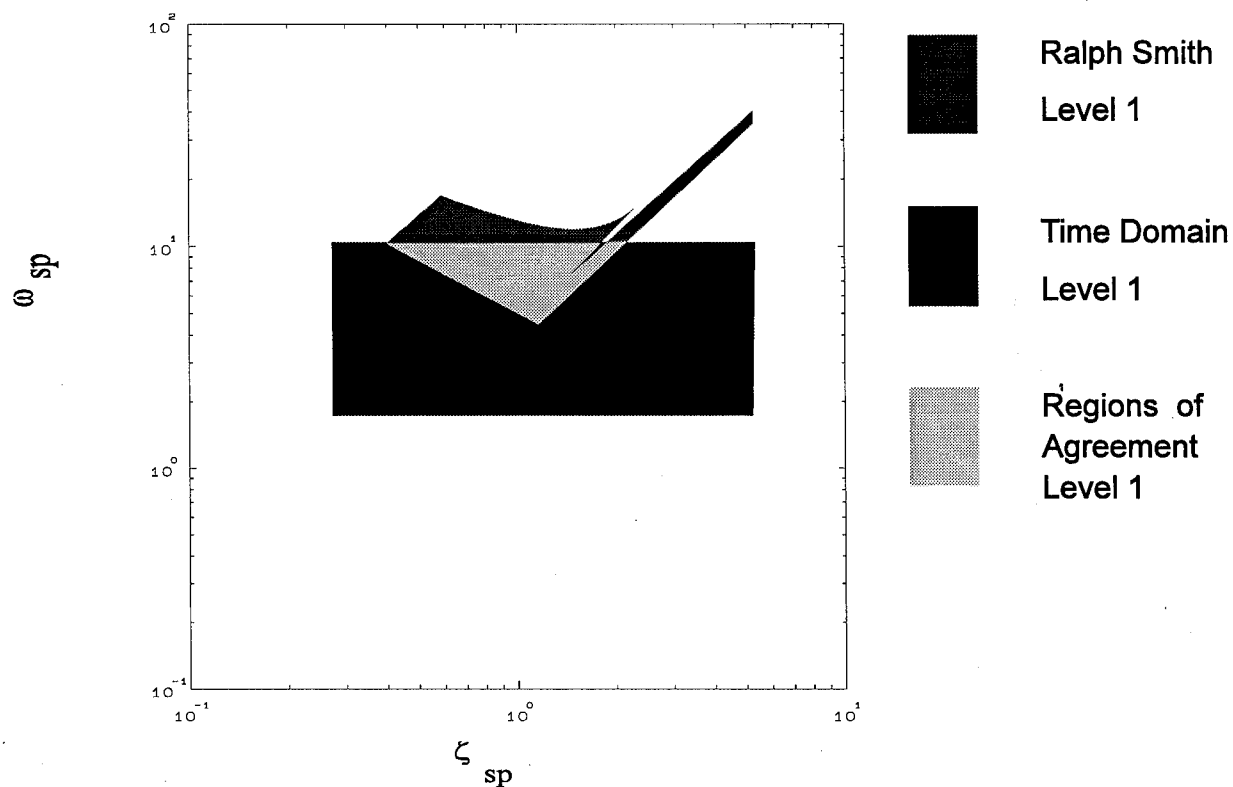


Figure C.27: Level 1 Regions (Case 5)

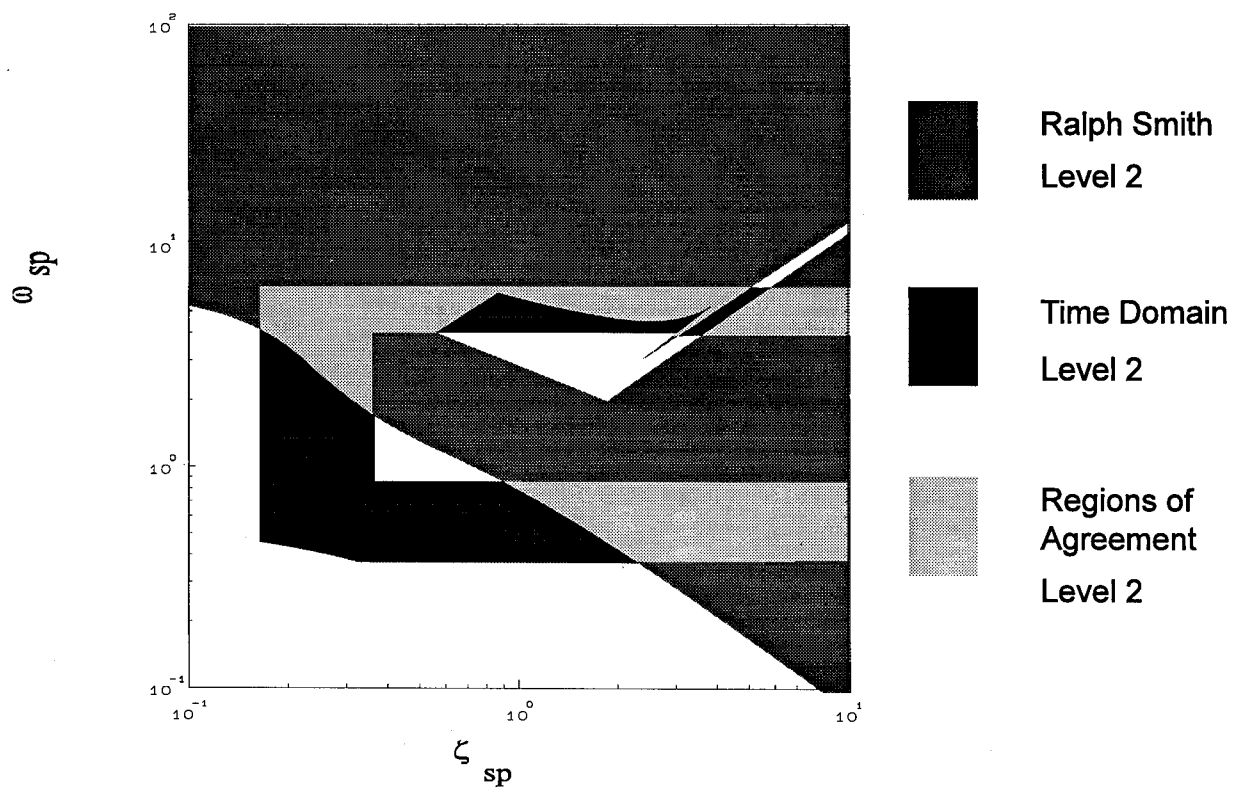


Figure C.28: Level 2 Regions (Case 5)

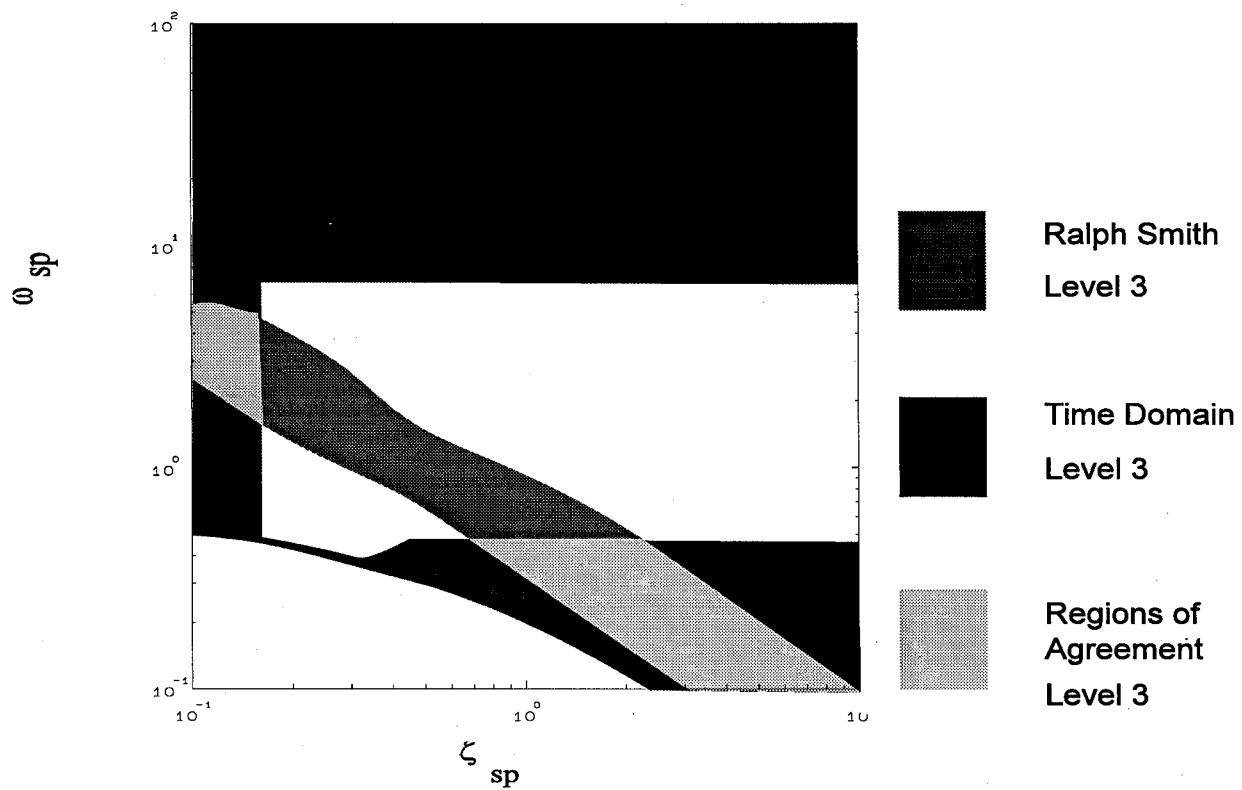


Figure C.29: Level 3 Regions (Case 5)

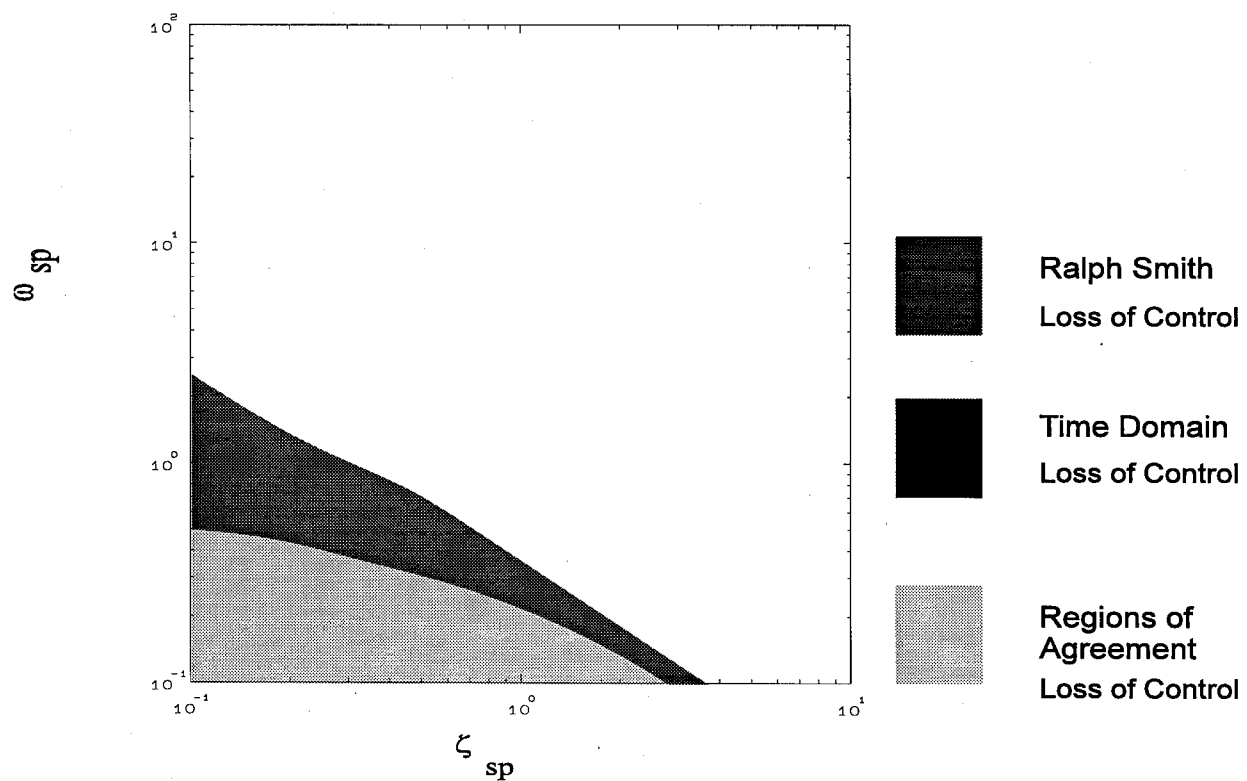


Figure C.30: Loss of Control Regions (Case 5)

C.6 Case 6

$$\frac{\theta(s)}{\delta(s)} = \frac{3.08(1.41s + 1)e^{-.1s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

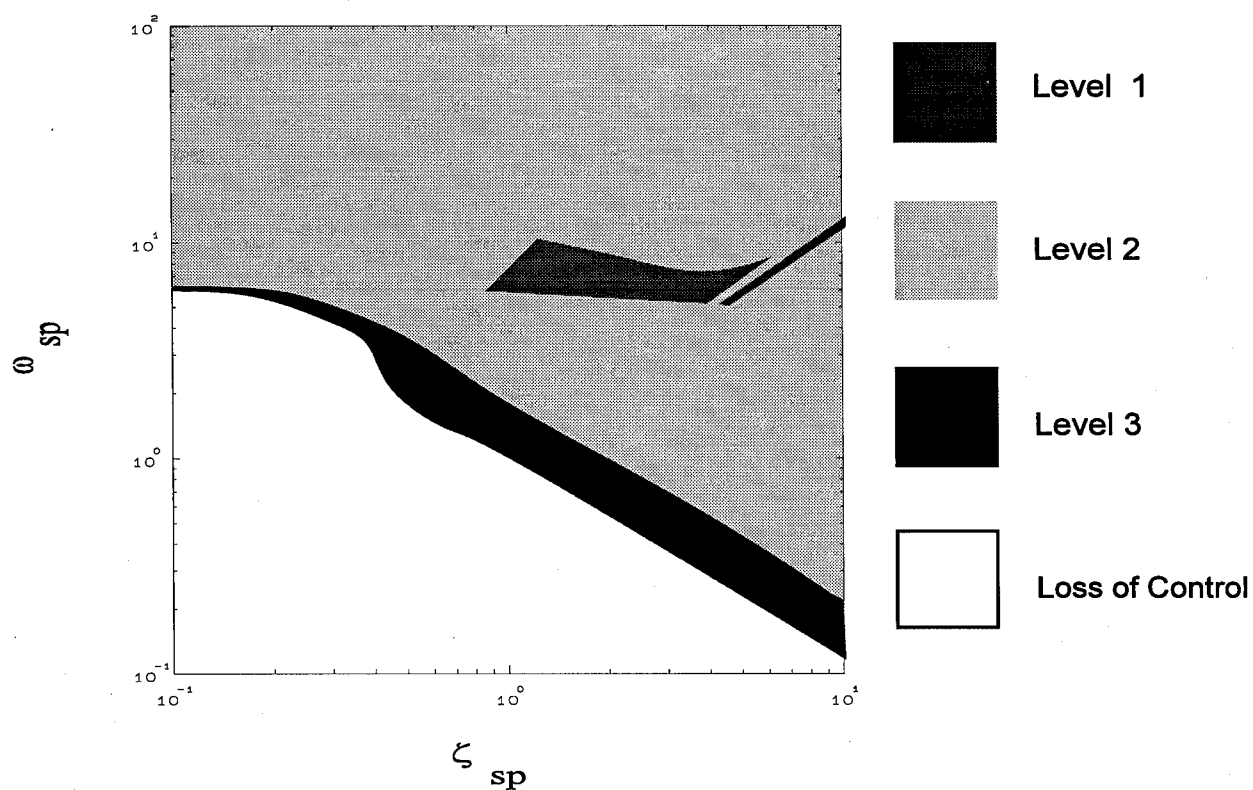


Figure C.31: Ralph Smith Criteria (Case 6)

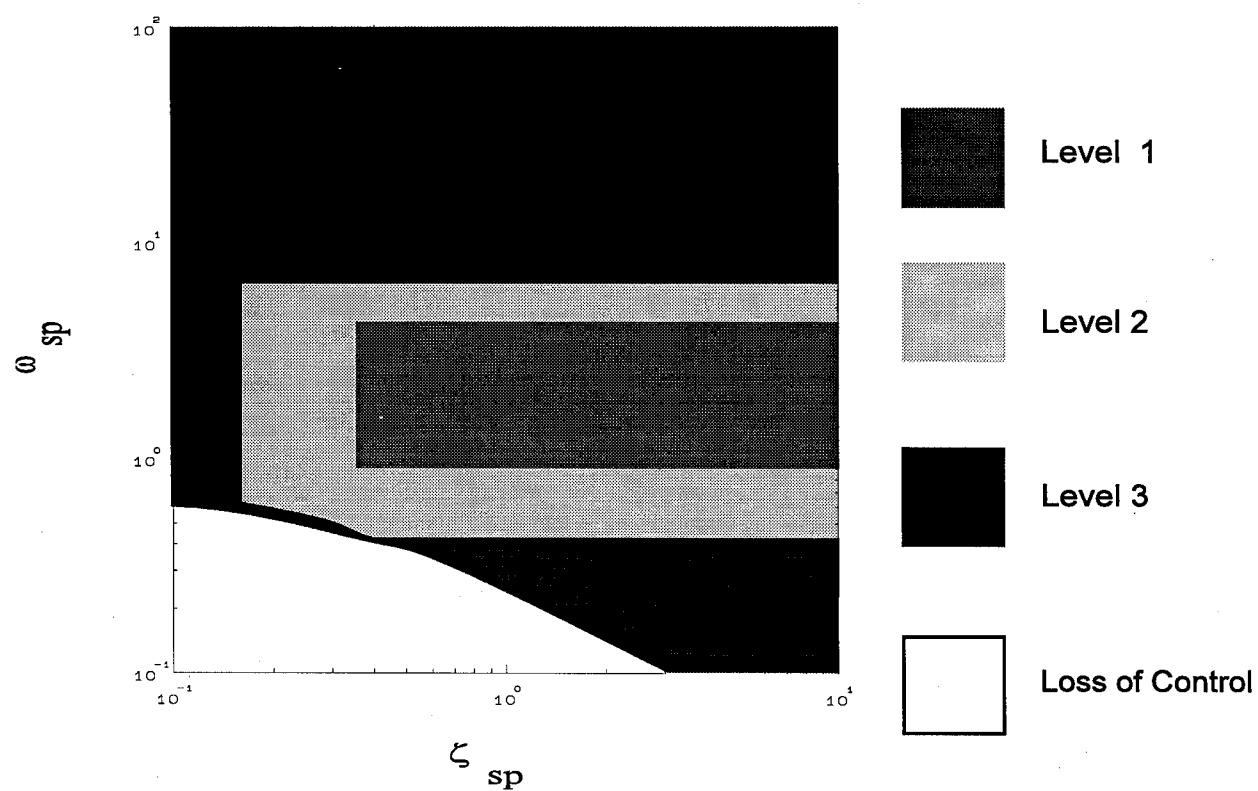
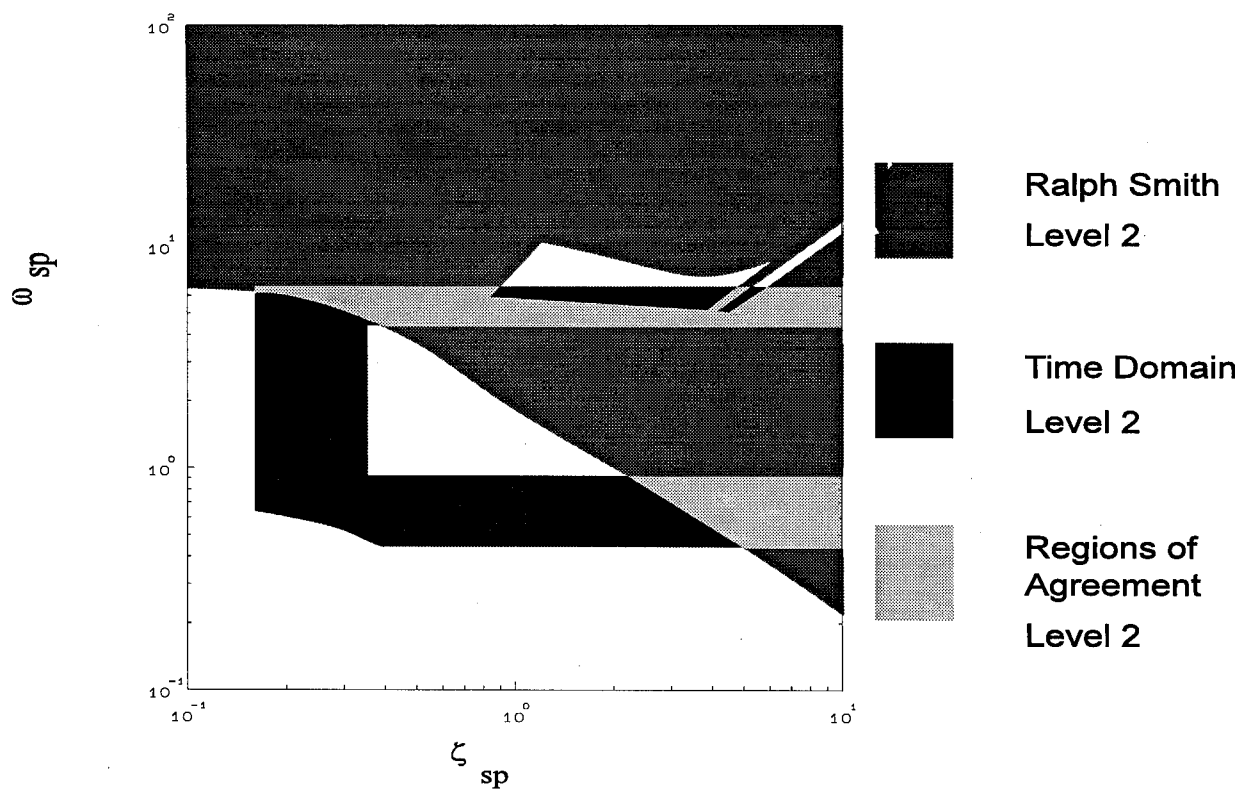
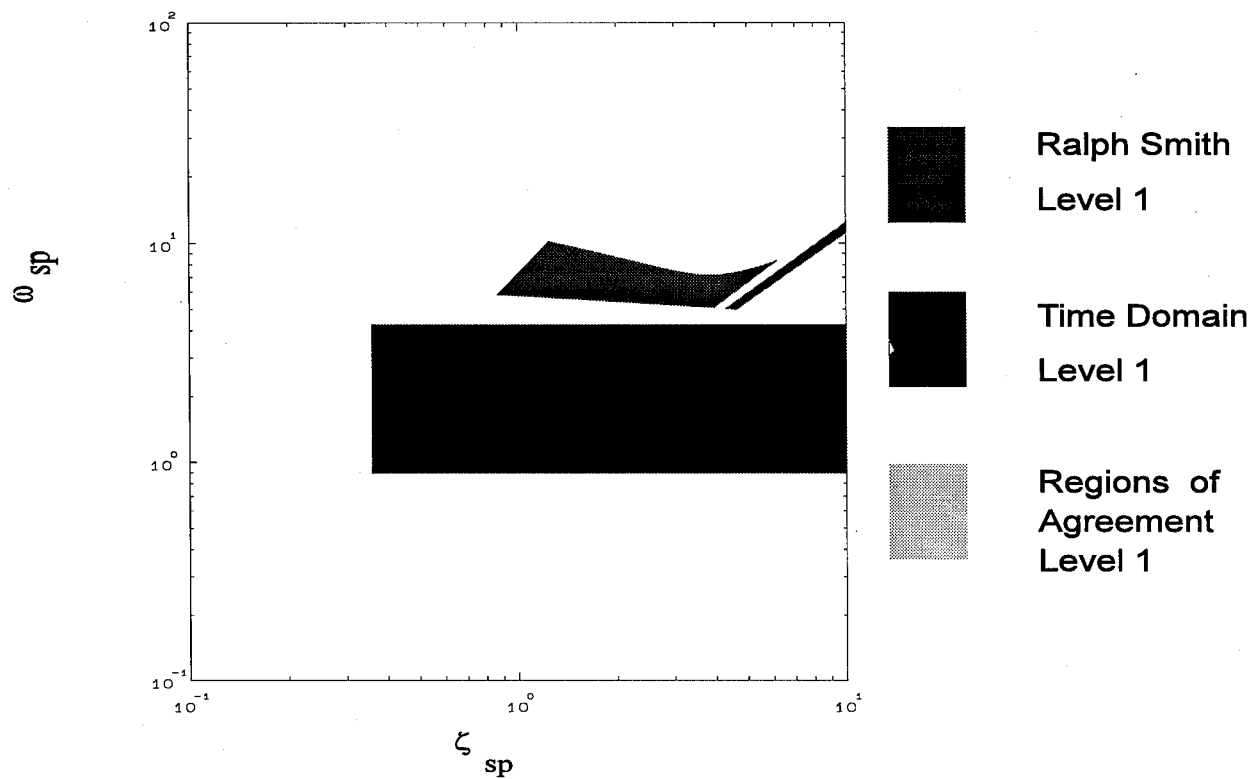


Figure C.32: Time Domain Criteria (Case 6)



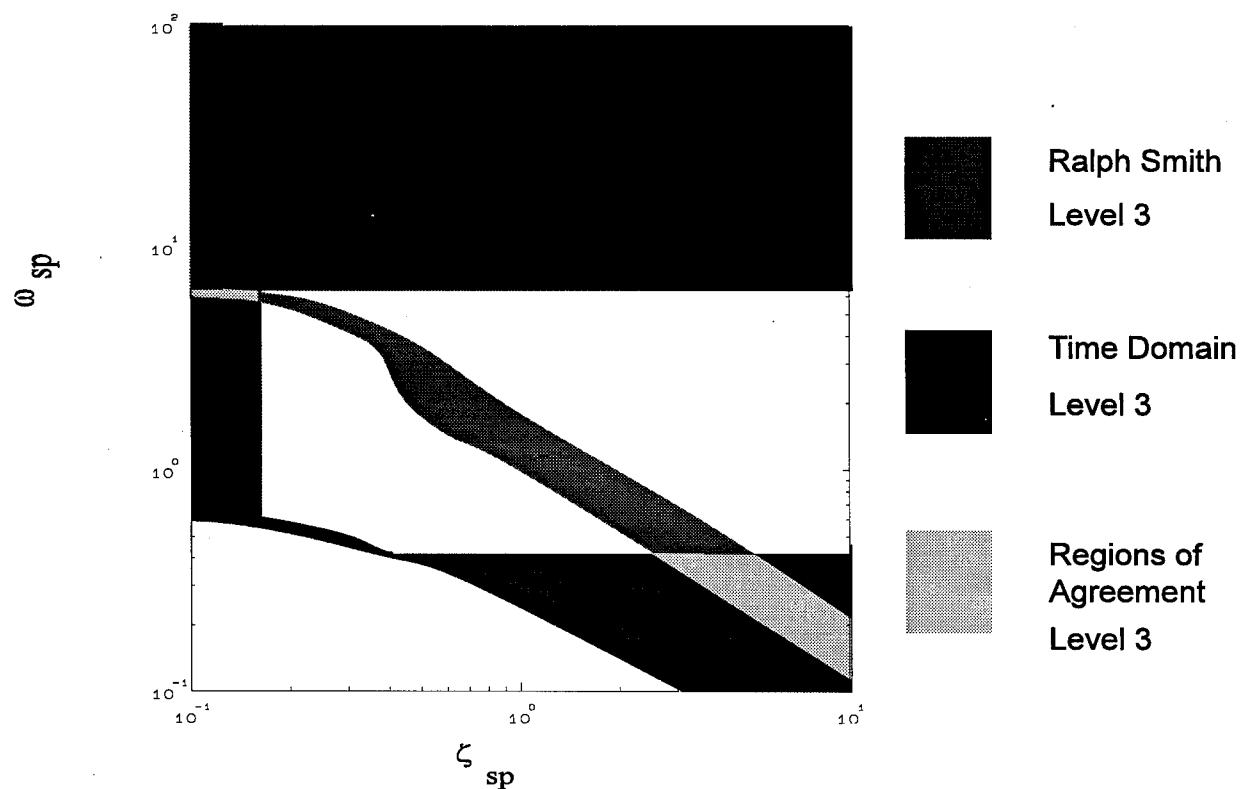


Figure C.35: Level 3 Regions (Case 6)

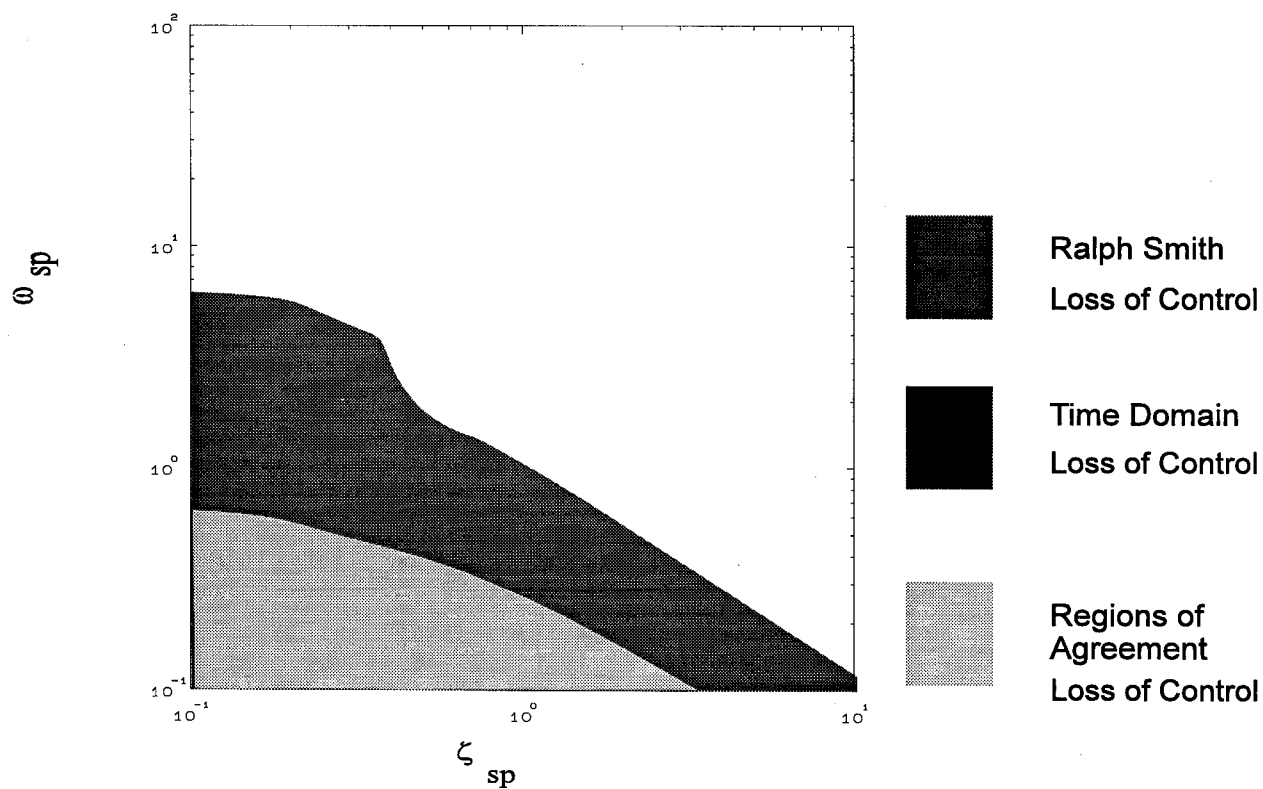


Figure C.36: Loss of Control Regions (Case 6)

C.7 Case 7

$$\frac{\theta(s)}{\delta(s)} = \frac{3.08(1.41s + 1)e^{-.15s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

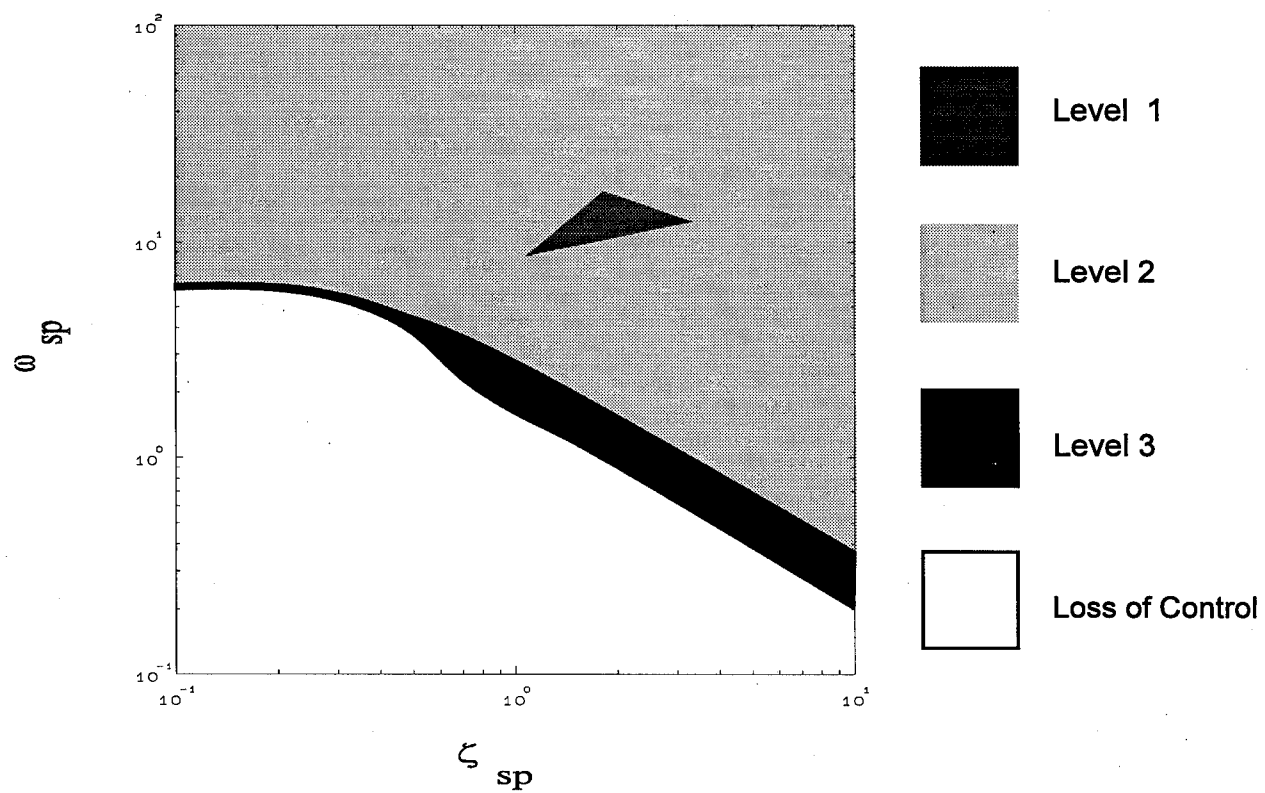


Figure C.37: Ralph Smith Criteria (Case 7)

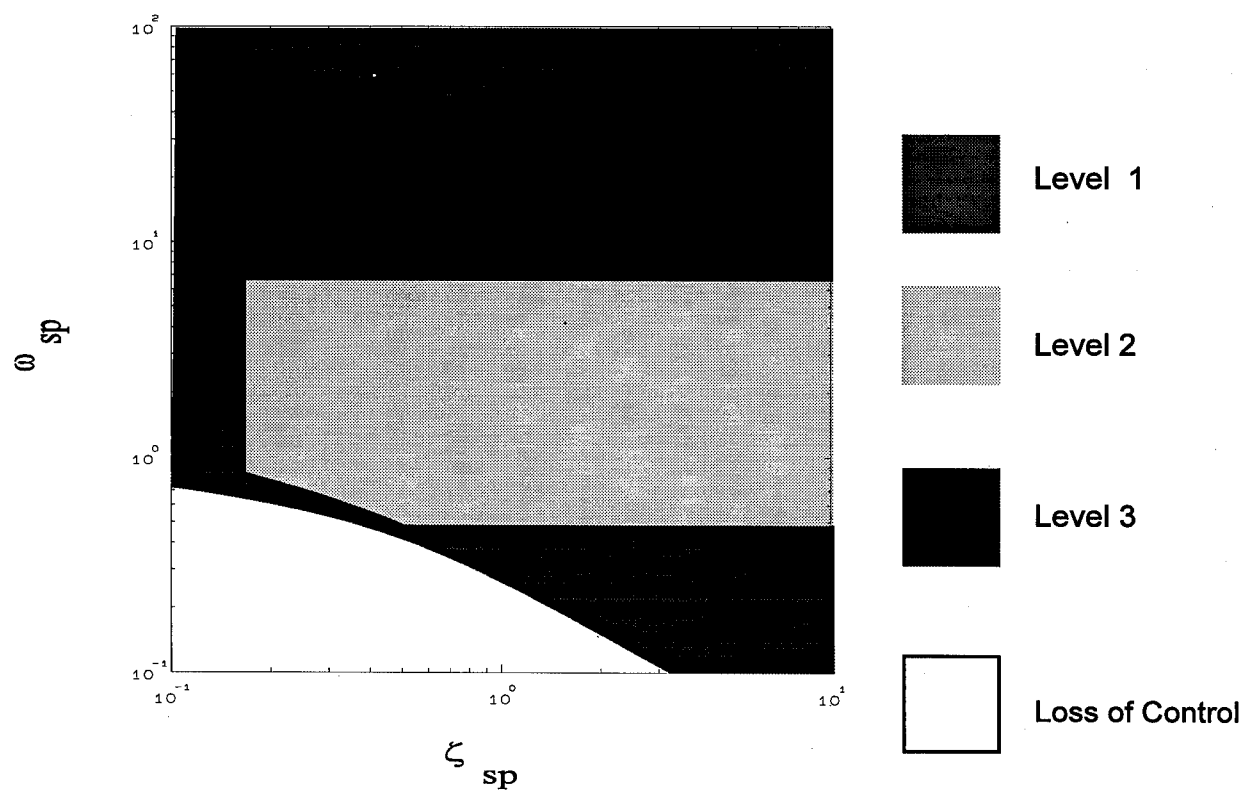


Figure C.38: Time Domain Criteria (Case 7)

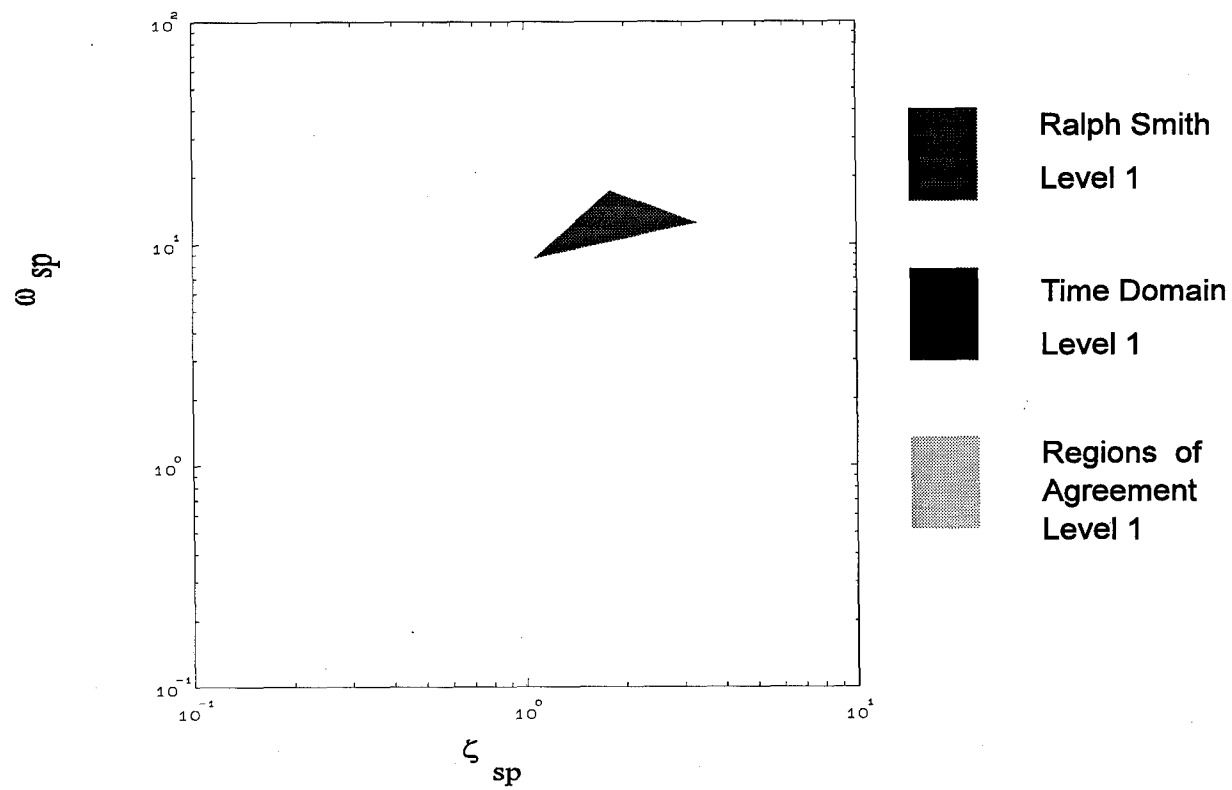


Figure C.39: Level 1 Regions (Case 7)

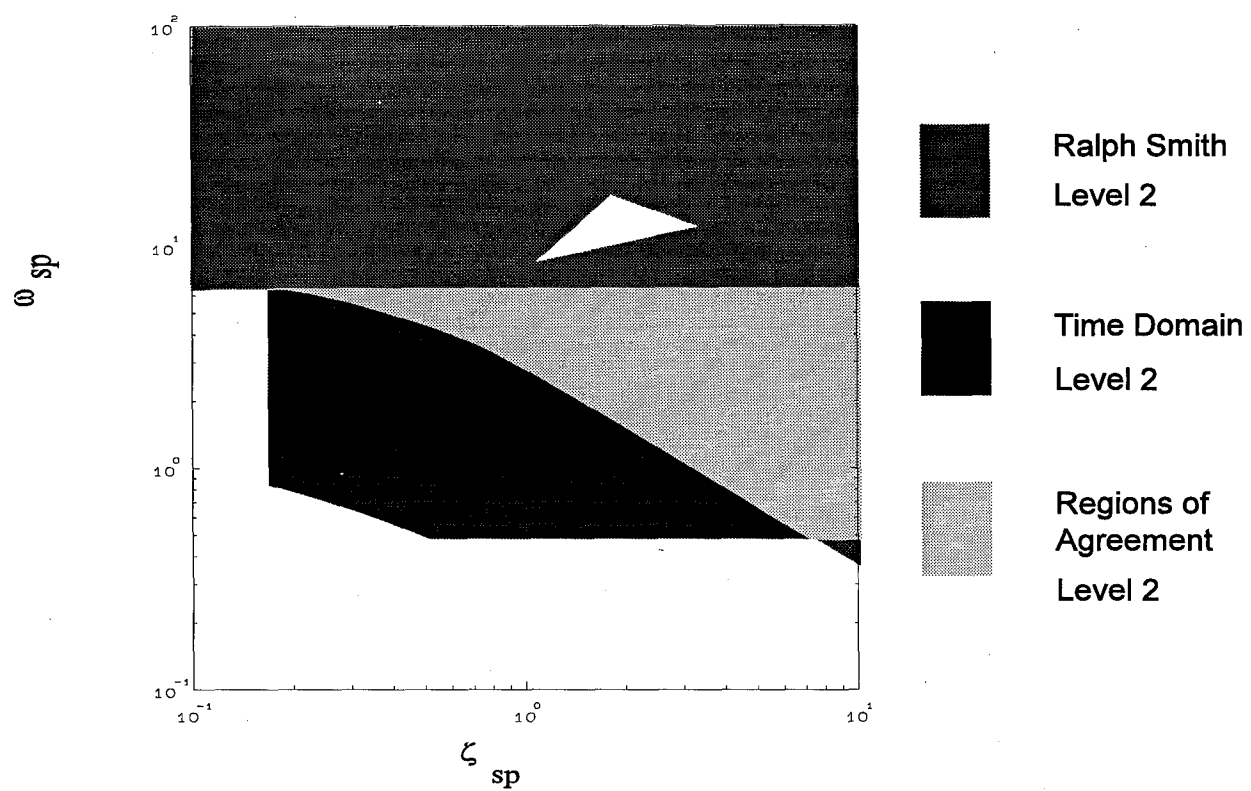


Figure C.40: Level 2 Regions (Case 7)

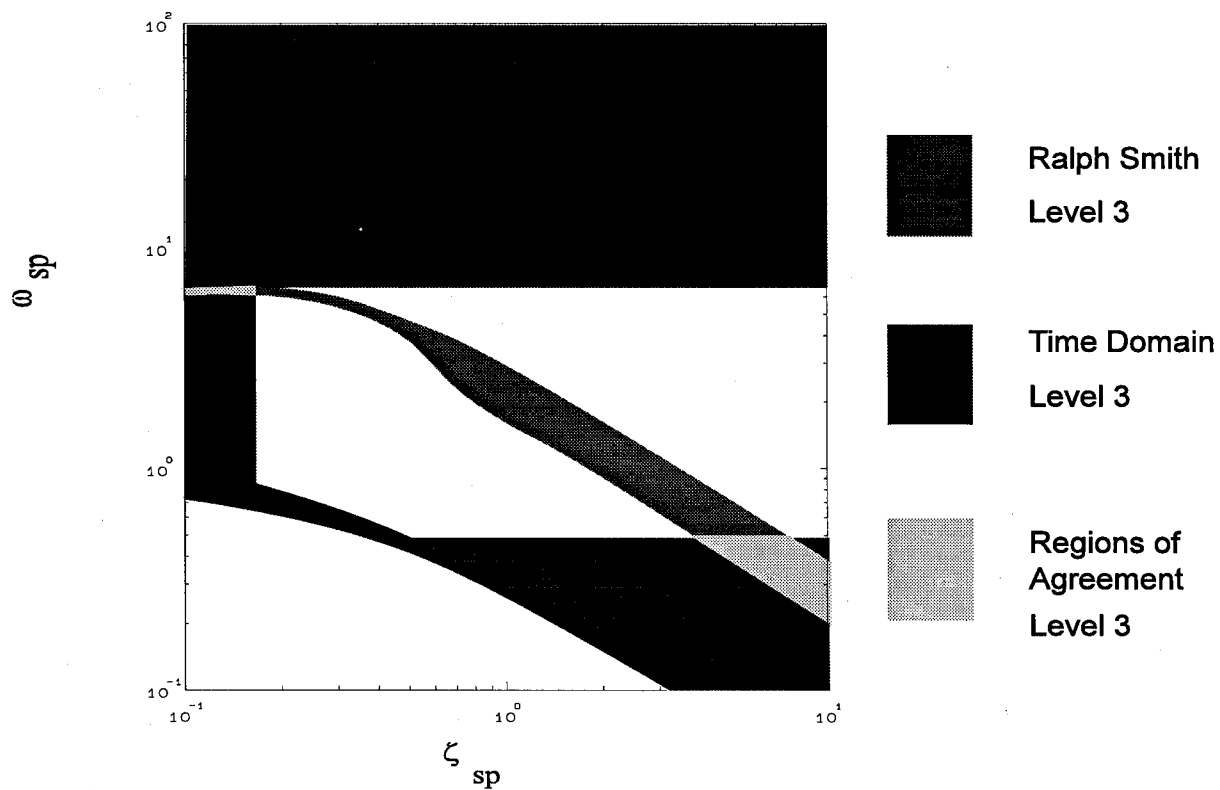


Figure C.41: Level 3 Regions (Case 7)

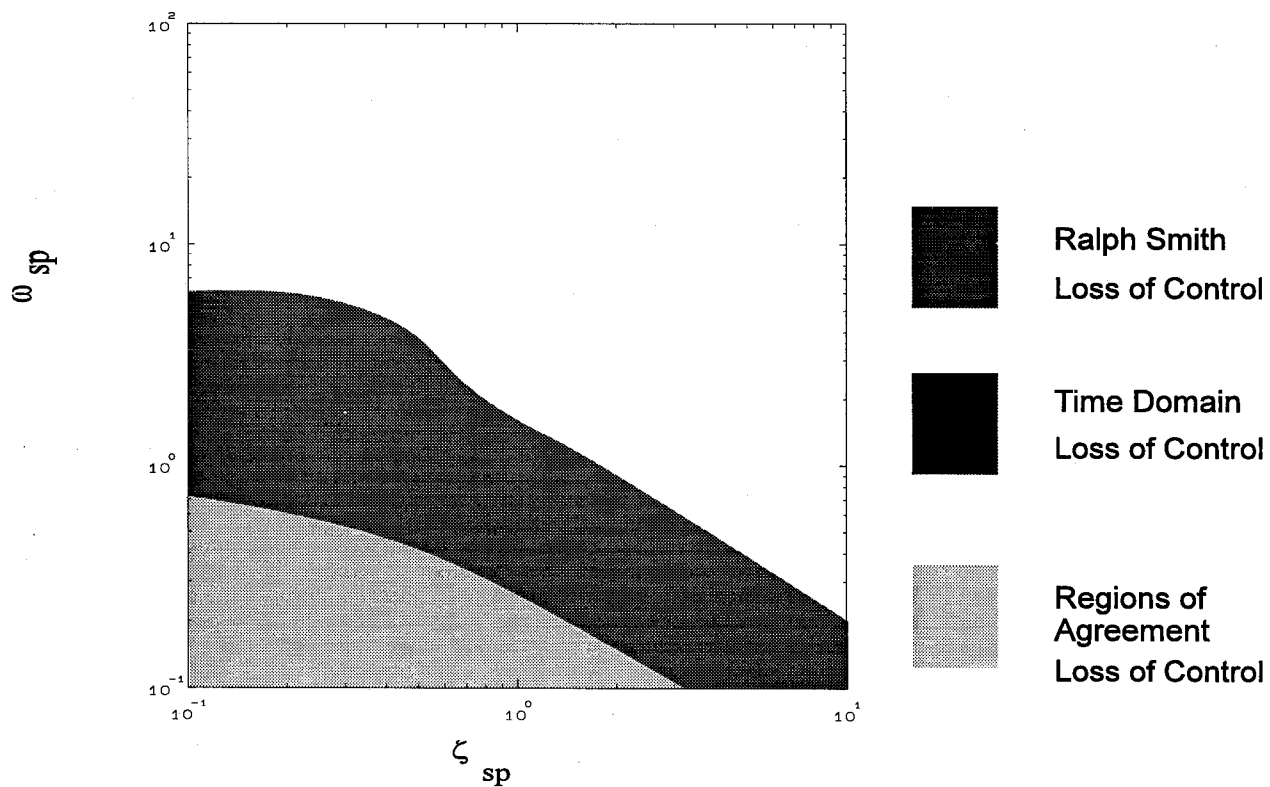


Figure C.42: Loss of Control Regions (Case 7)

C.8 Case 8

$$\frac{\theta(s)}{\delta(s)} = \frac{3.08(1.41s + 1)e^{-.2s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

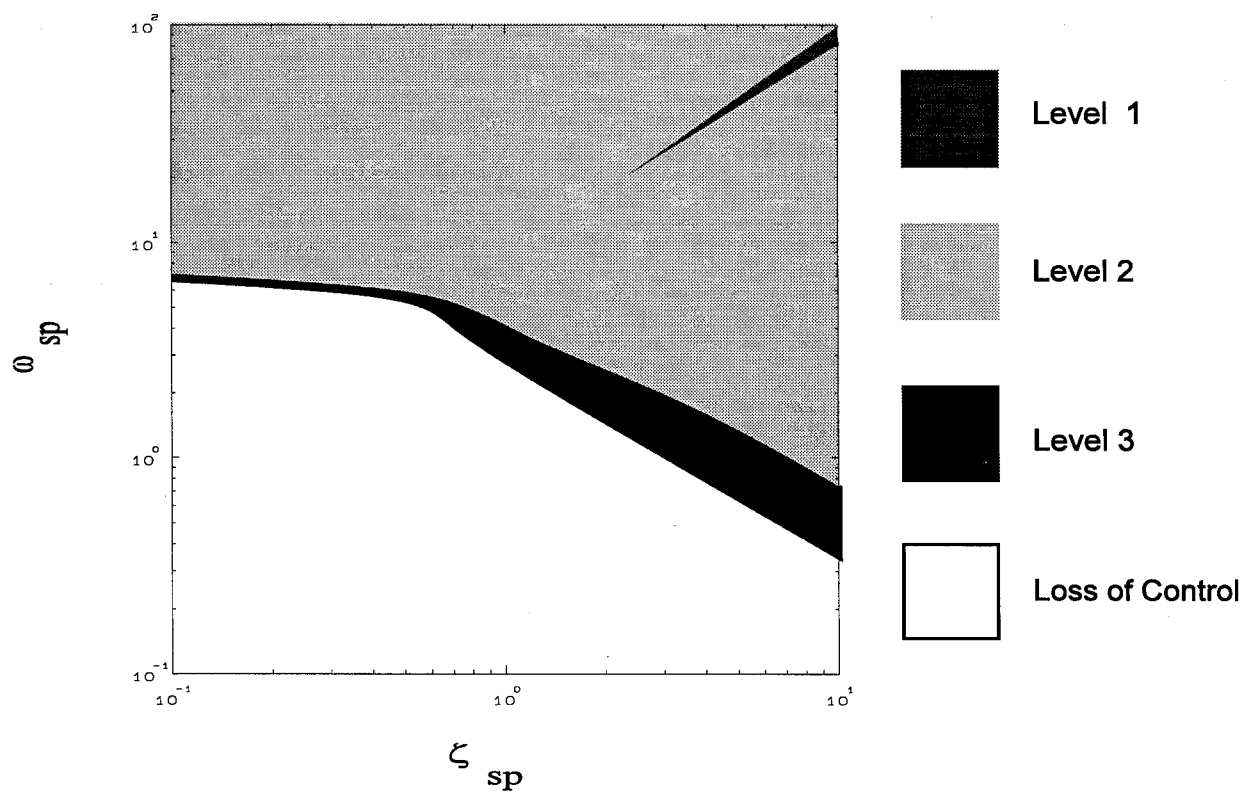


Figure C.43: Ralph Smith Criteria (Case 8)

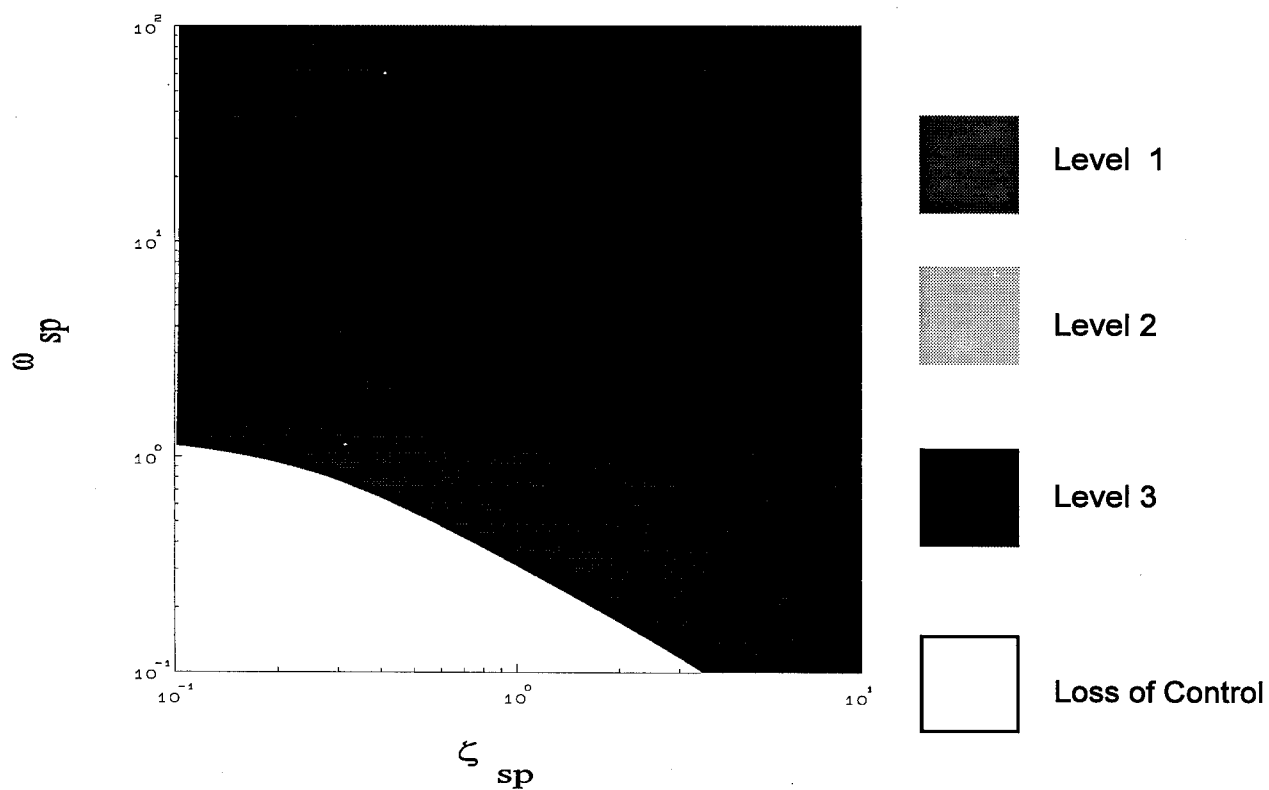


Figure C.44: Time Domain Criteria (Case 8)

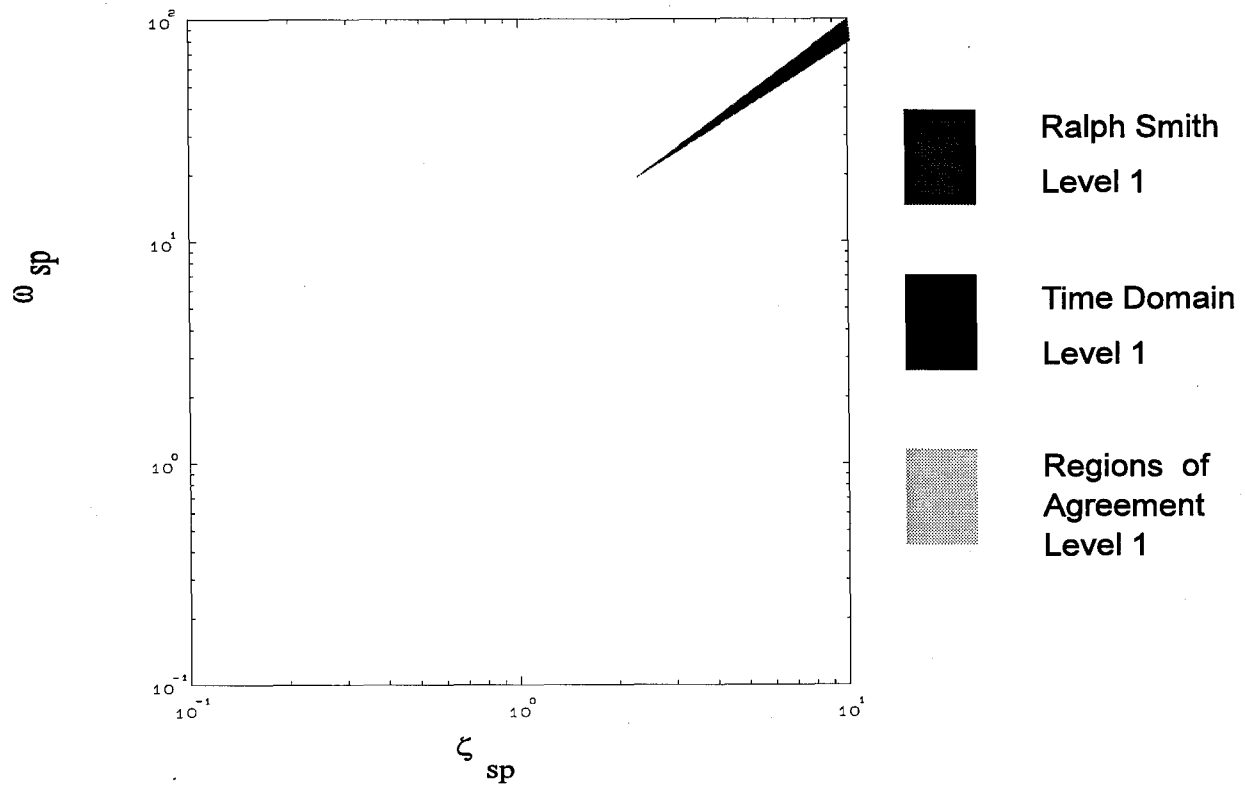


Figure C.45: Level 1 Regions (Case 8)

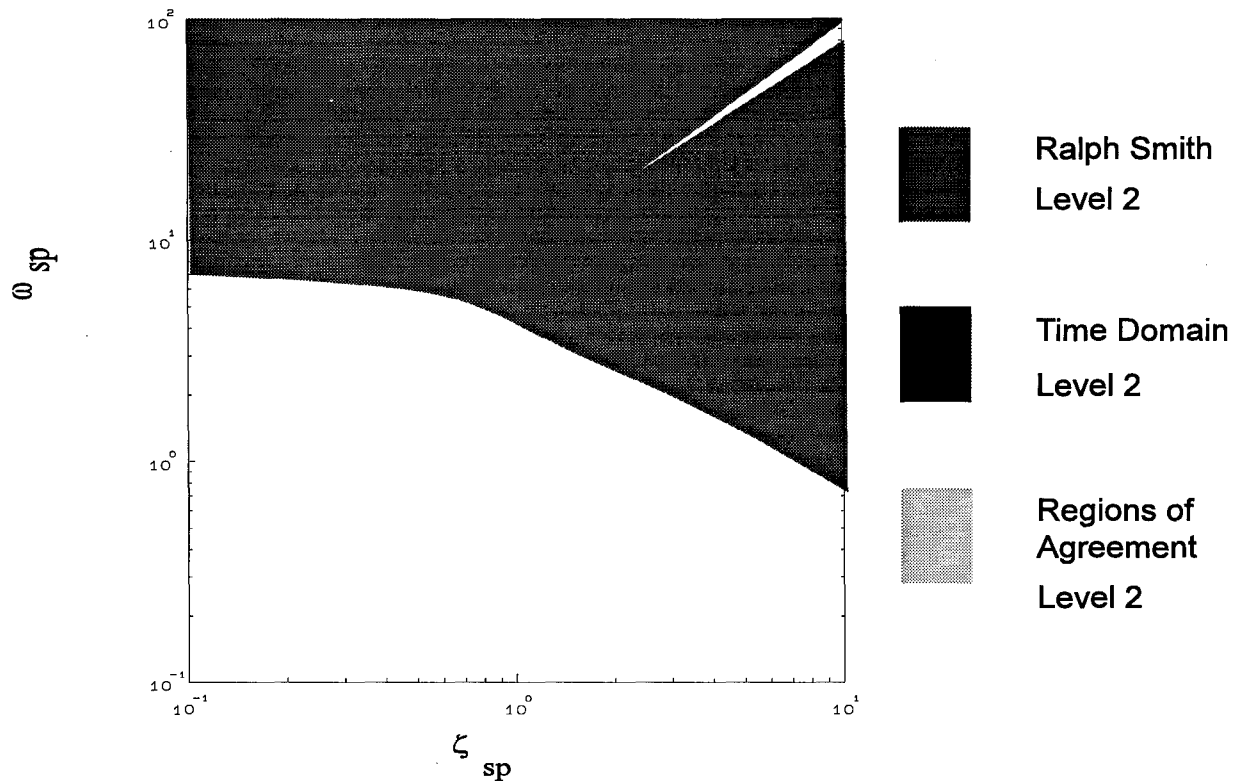


Figure C.46: Level 2 Regions (Case 8)

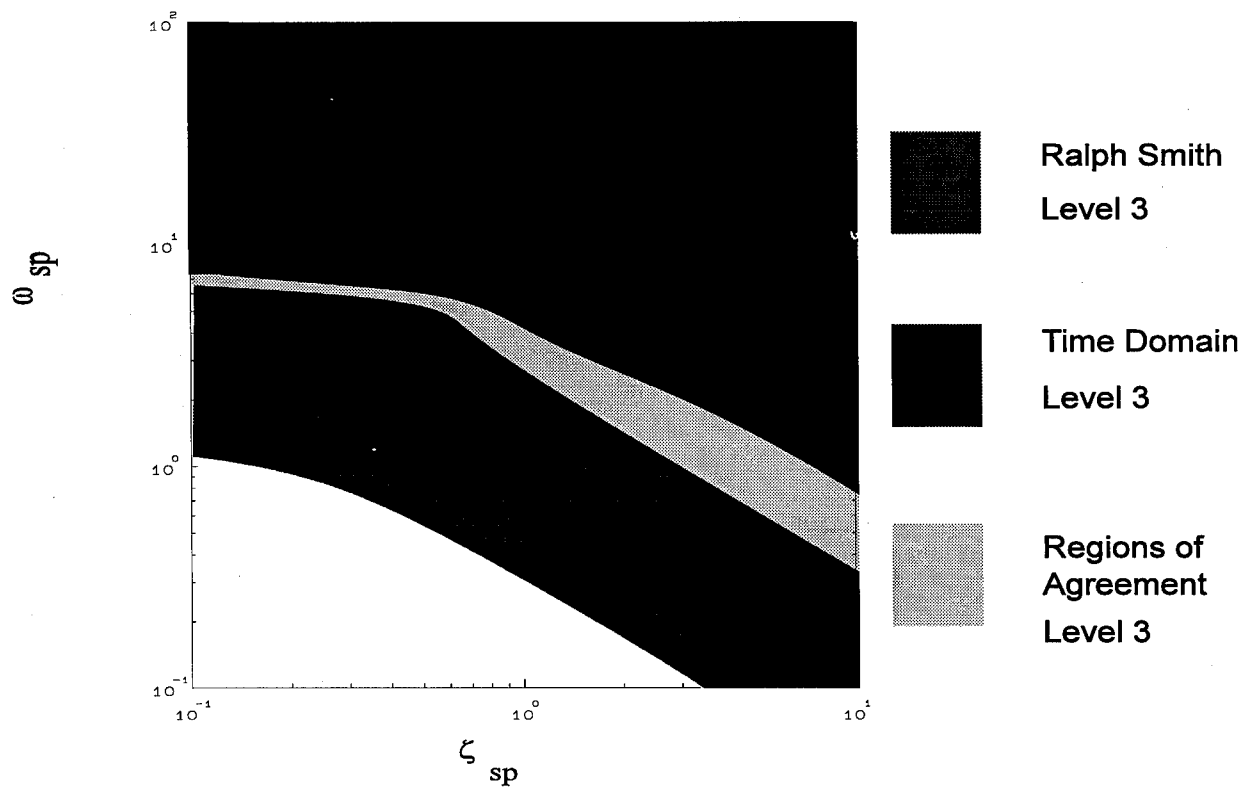


Figure C.47: Level 3 Regions (Case 8)

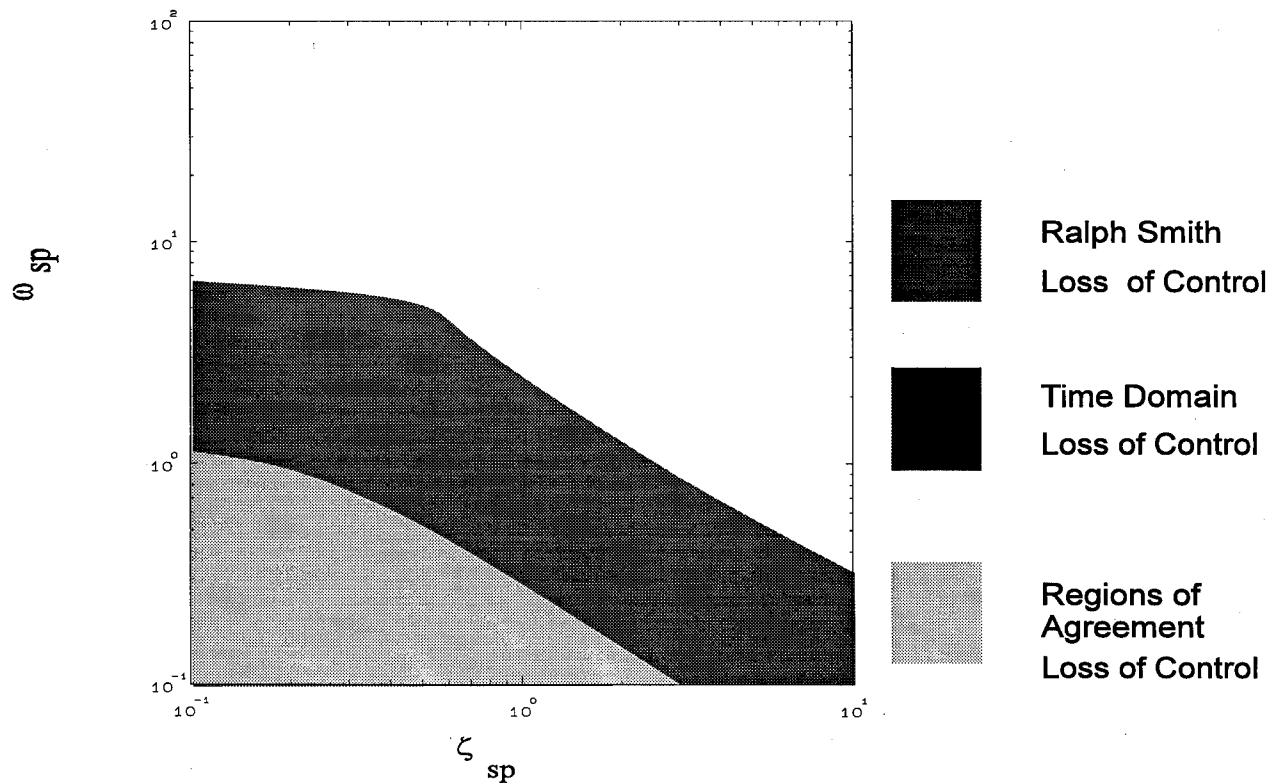


Figure C.48: Loss of Control Regions (Case 8)

C.9 Case 9

Lear Jet Transfer Function III

$$\frac{\theta(s)}{\delta(s)} = \frac{3.9897(1.32s + 1)e^{0s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

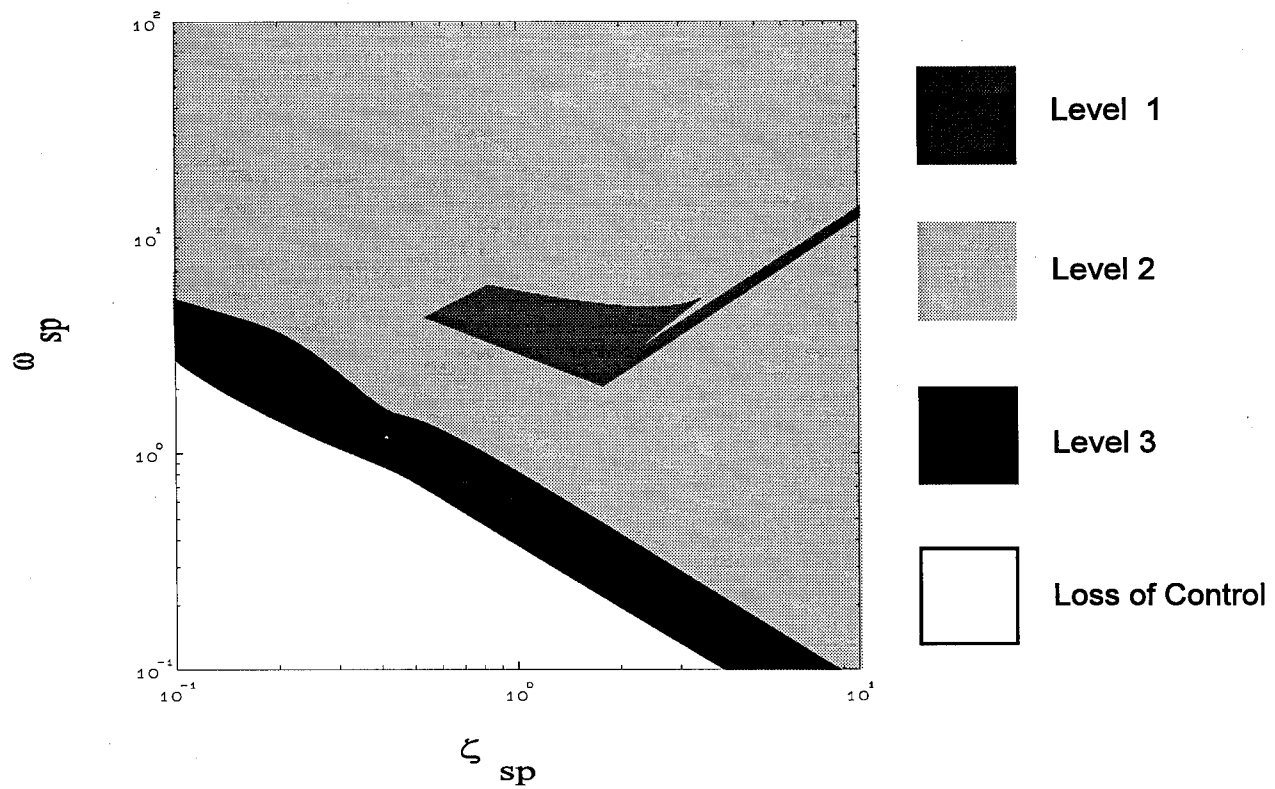


Figure C.49: Ralph Smith Criteria (Case 9)

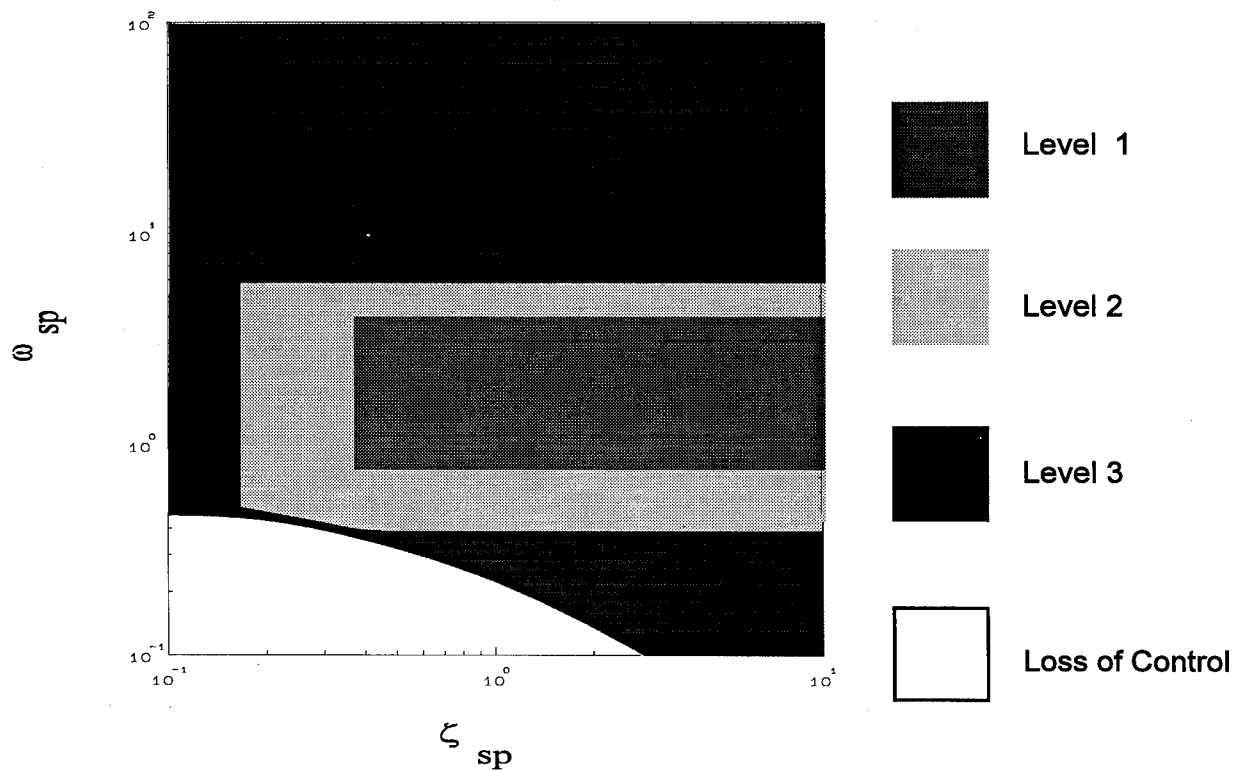


Figure C.50: Time Domain Criteria (Case 9)

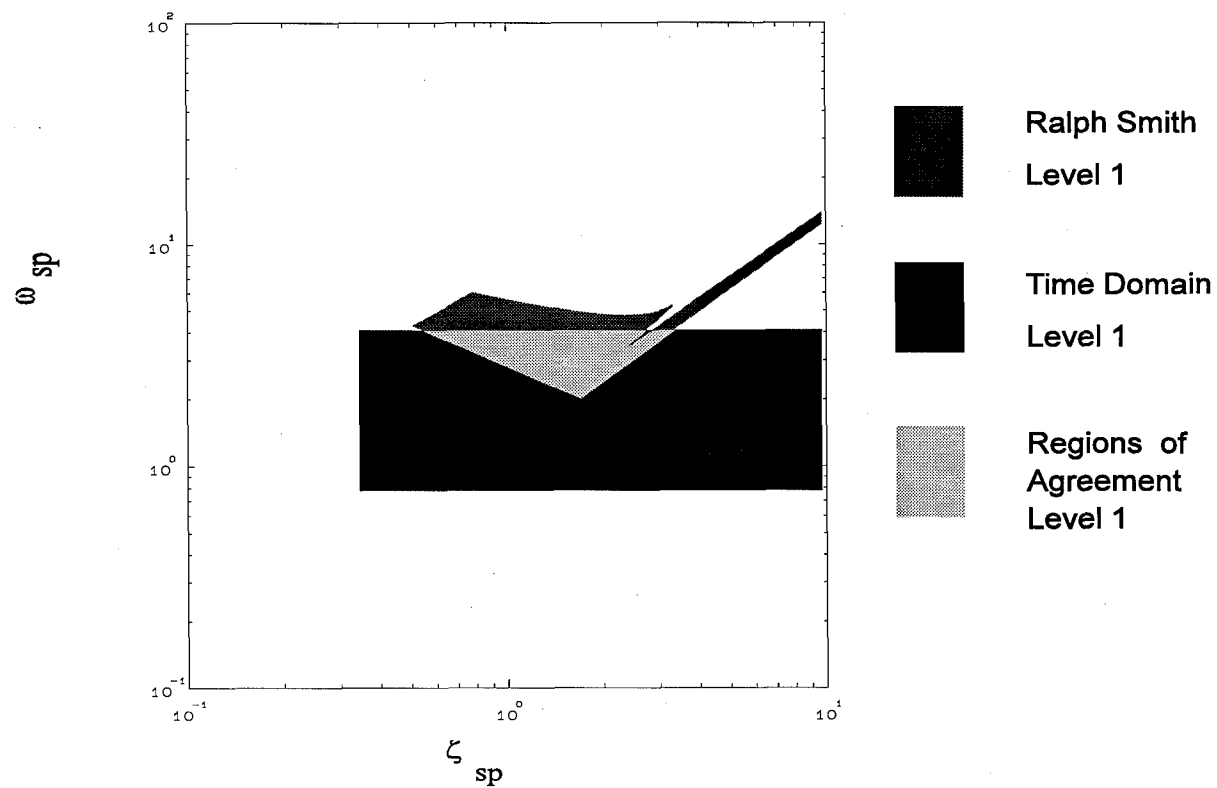


Figure C.51: Level 1 Regions (Case 9)

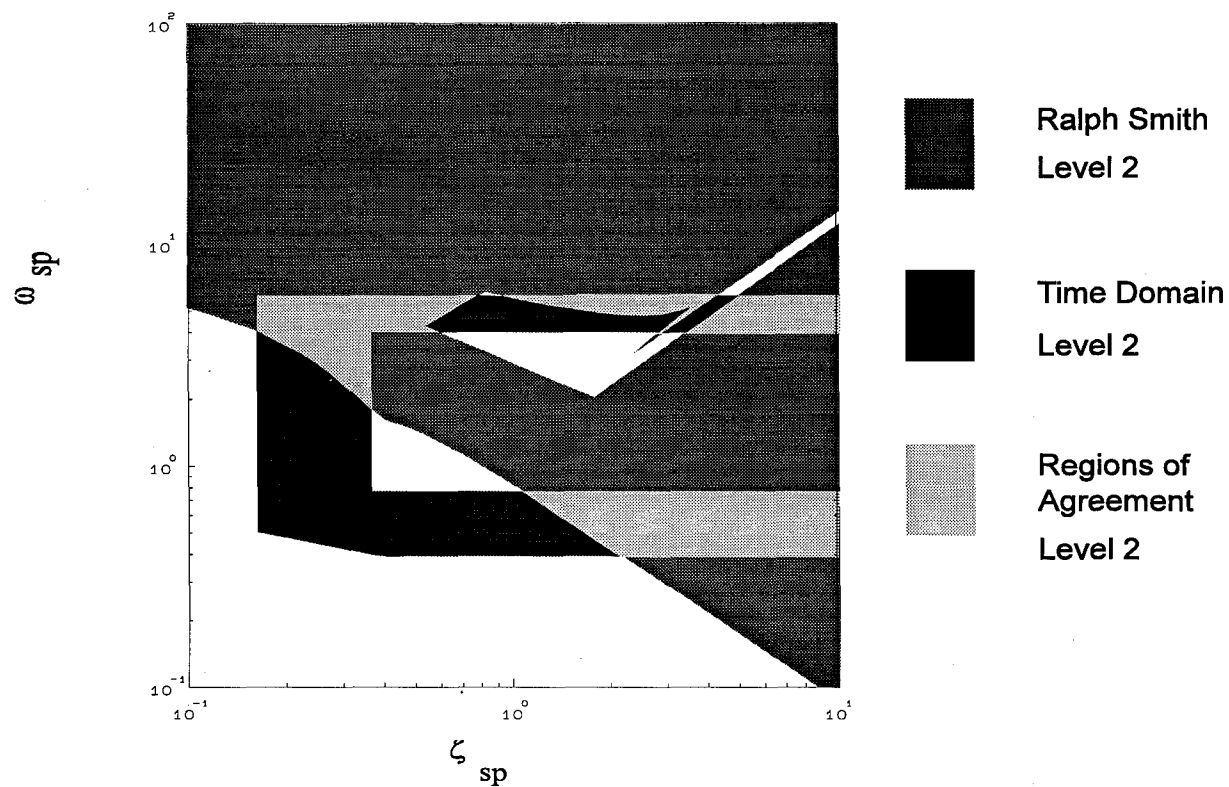


Figure C.52: Level 2 Regions (Case 9)

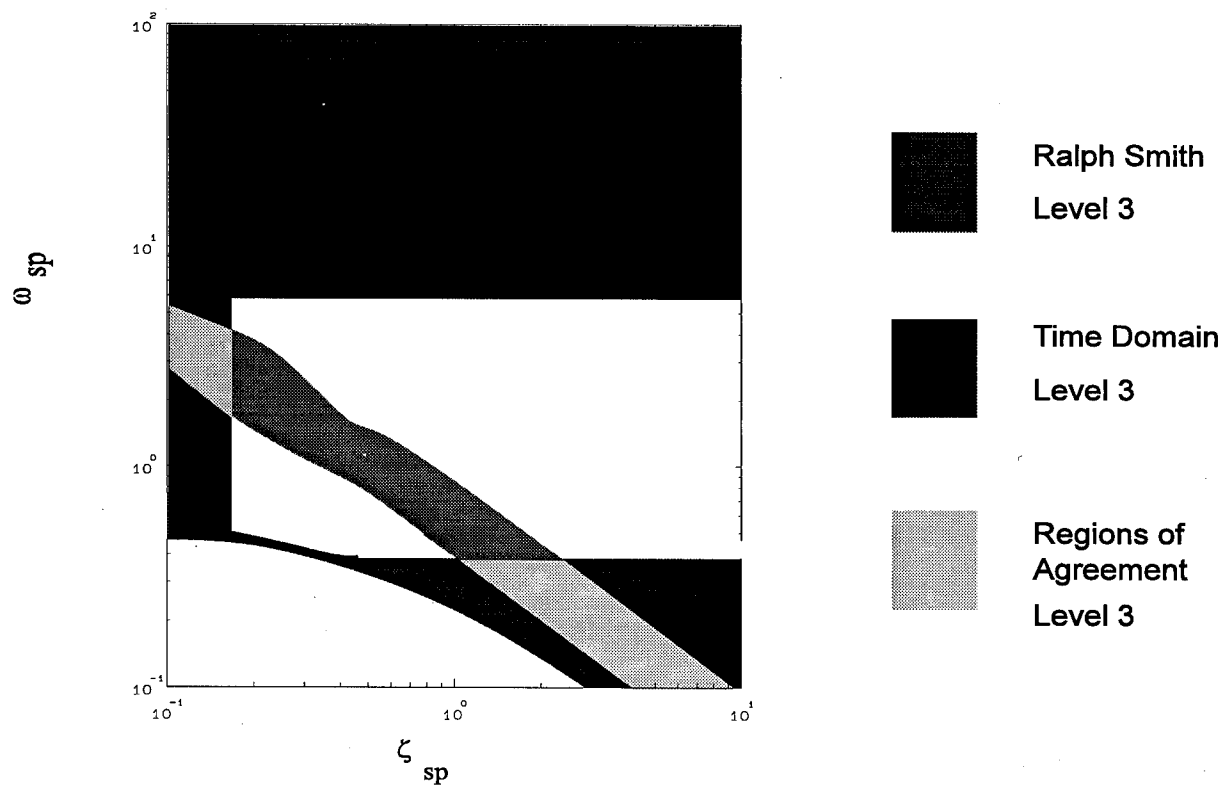


Figure C.53: Level 3 Regions (Case 9)

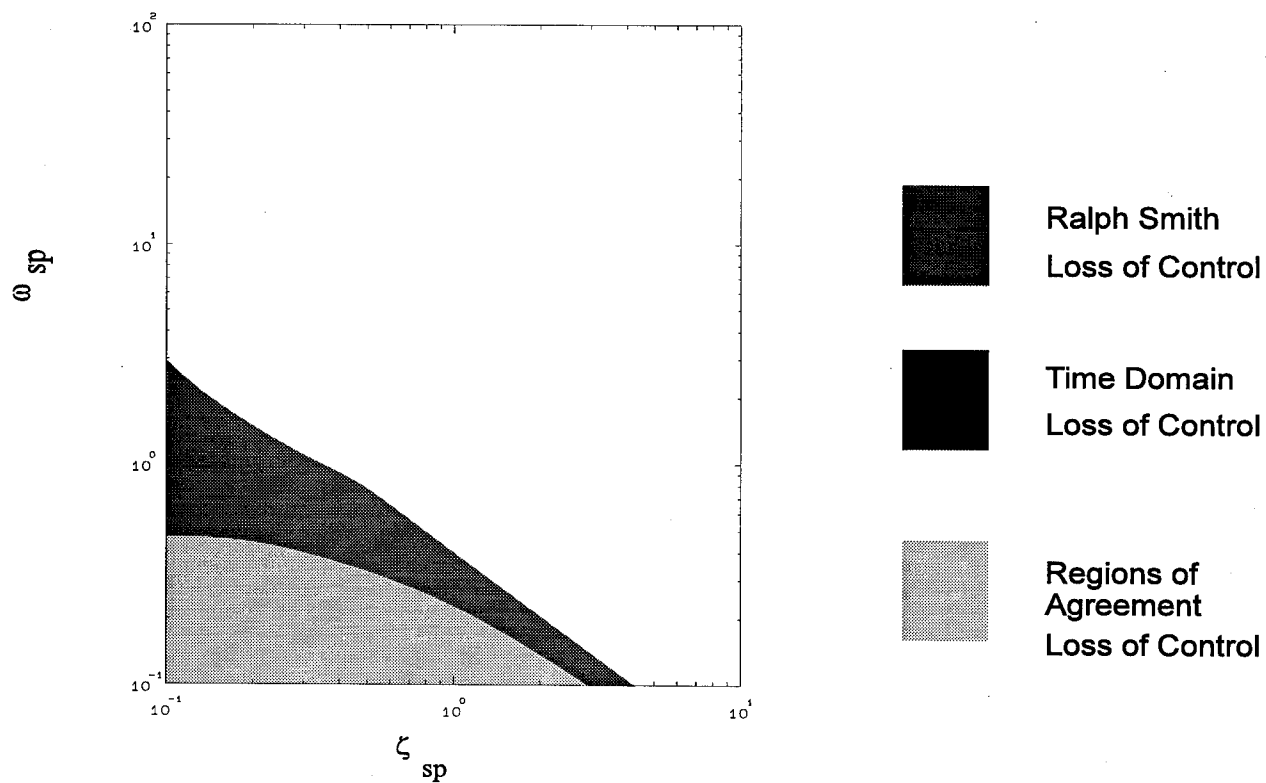


Figure C.54: Loss of Control Regions (Case 9)

C.10 Case 10

$$\frac{\theta(s)}{\delta(s)} = \frac{3.9897(1.32s + 1)e^{-.1s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

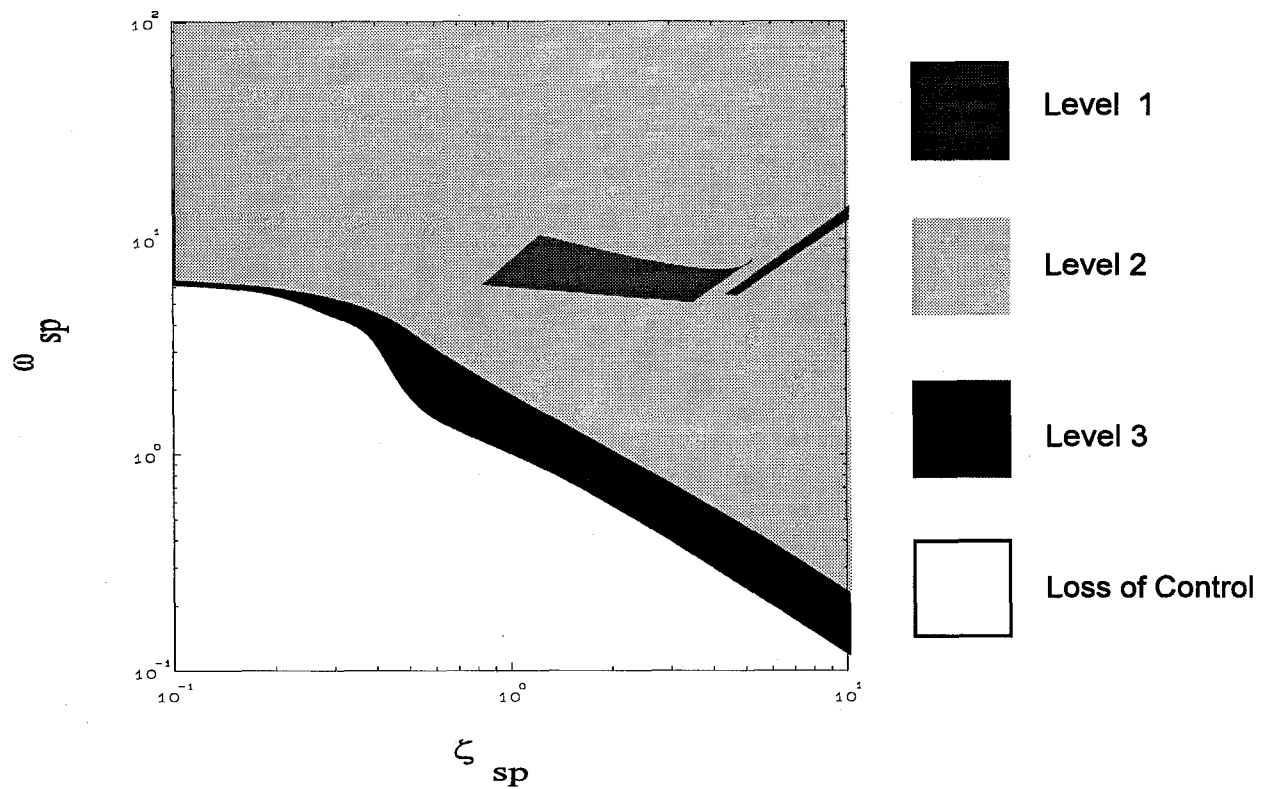


Figure C.55: Ralph Smith Criteria (Case 10)

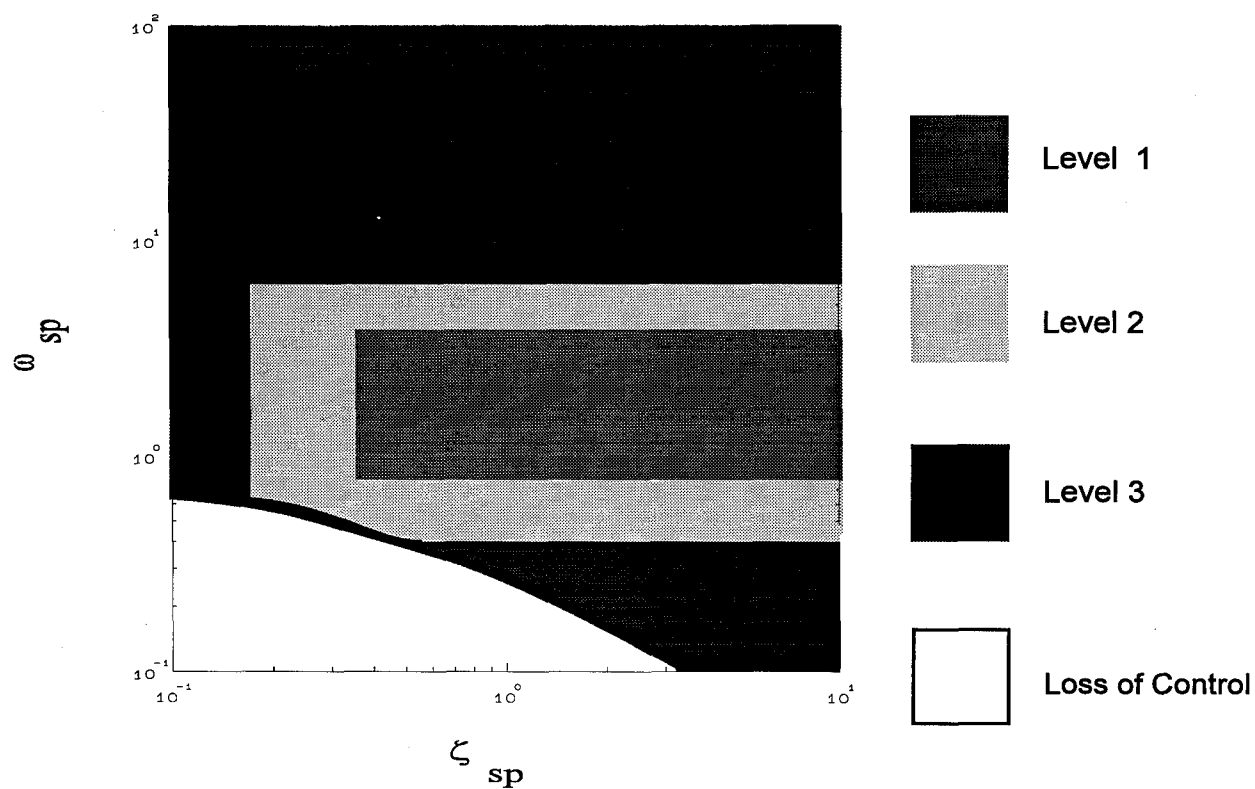


Figure C.56: Time Domain Criteria (Case 10)

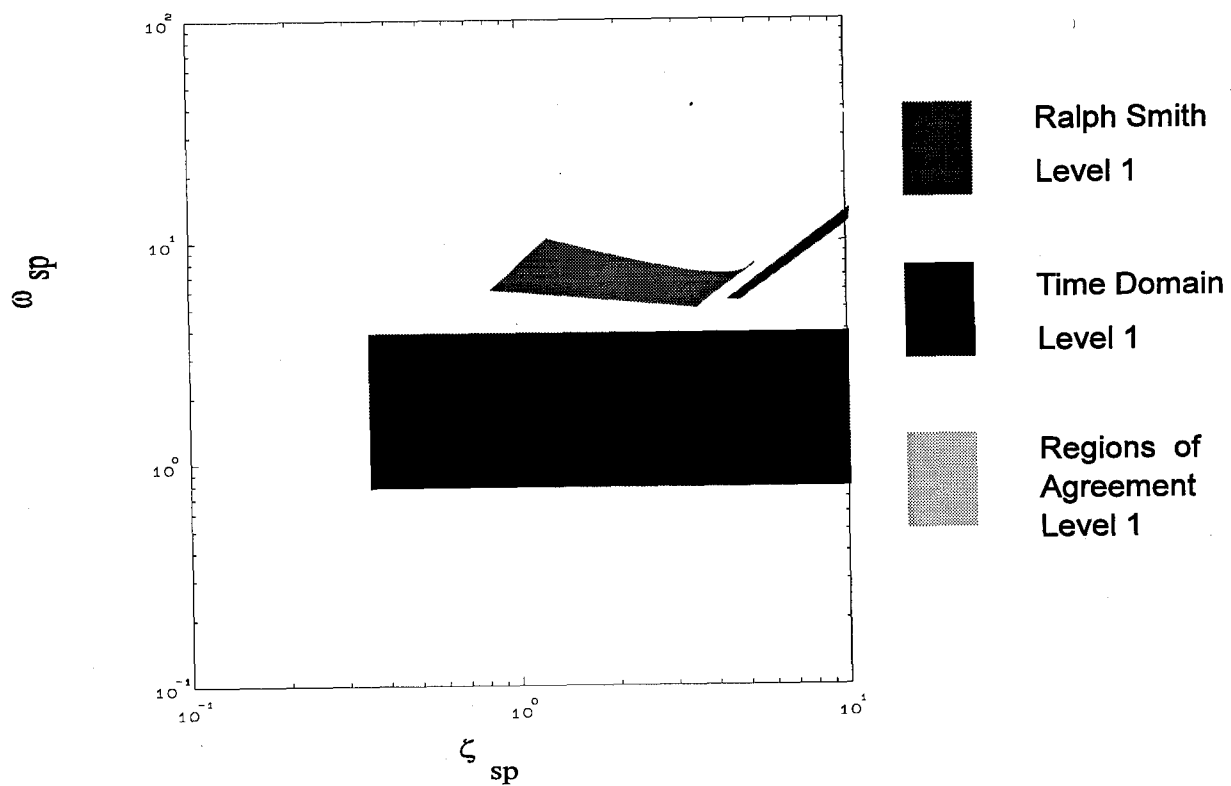


Figure C.57: Level 1 Regions (Case 10)

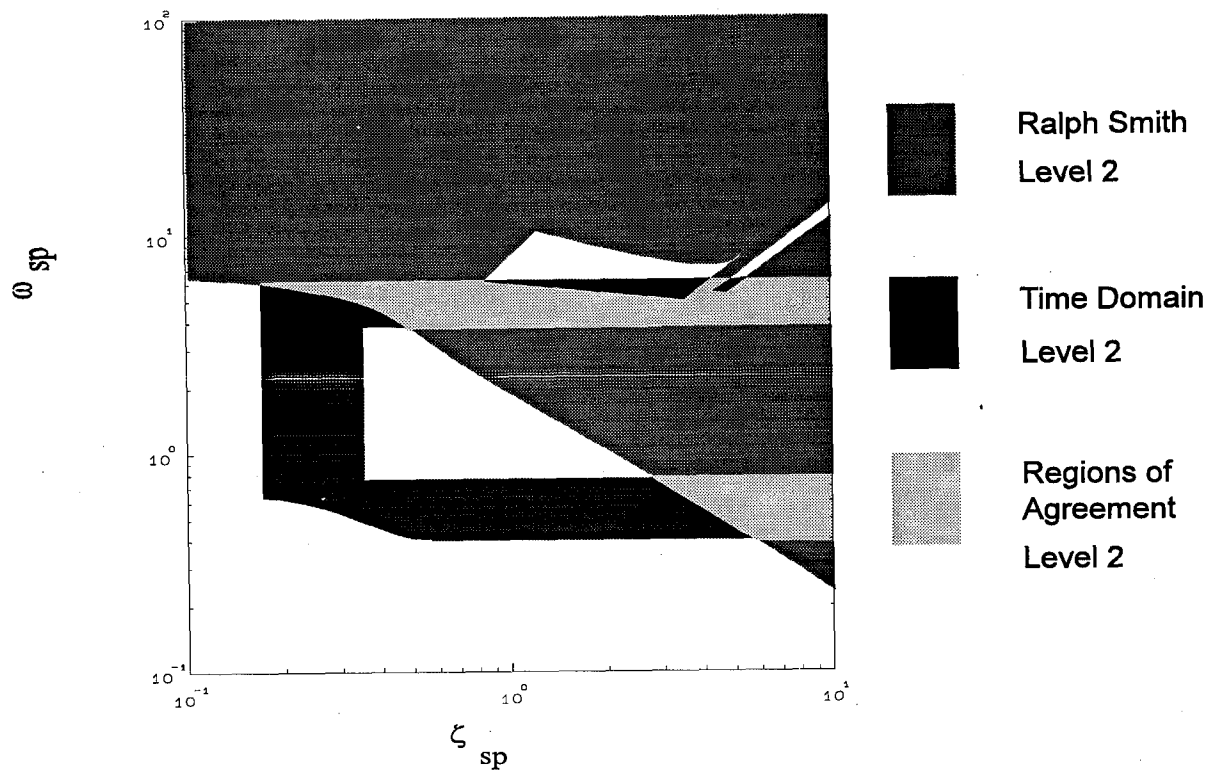


Figure C.58: Level 2 Regions (Case 10)

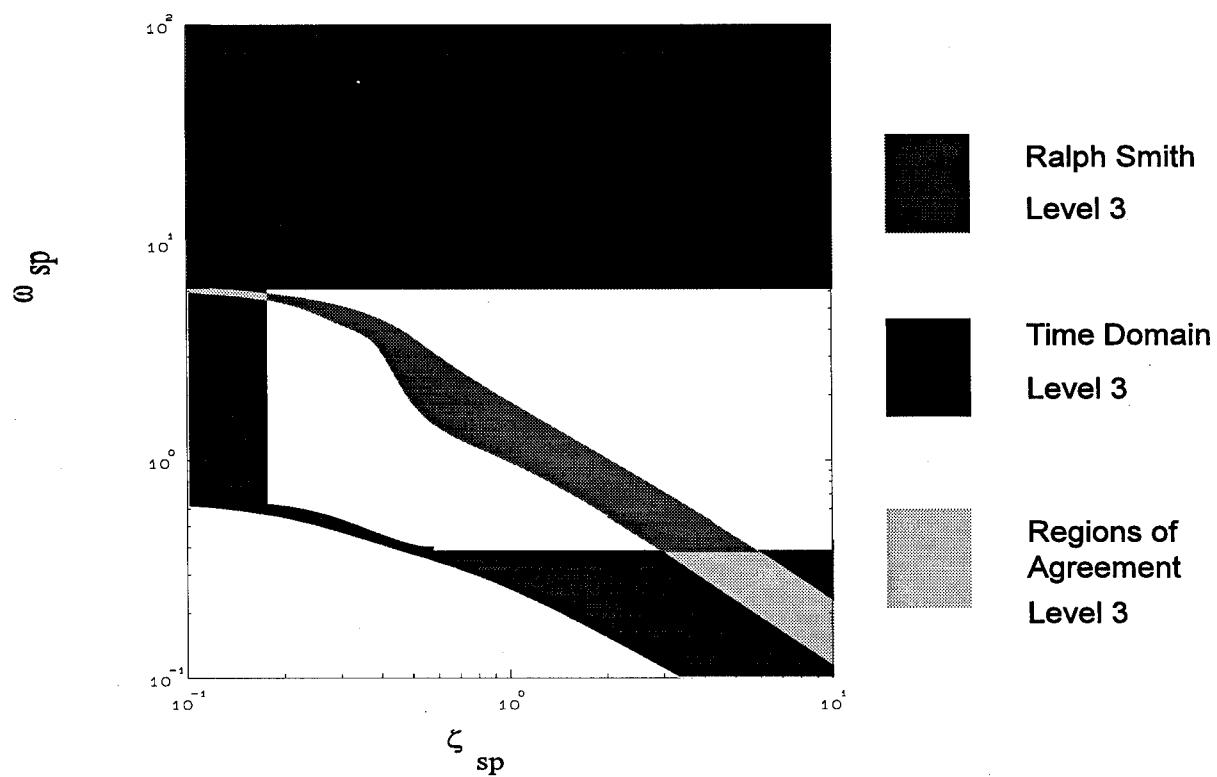


Figure C.59: Level 3 Regions (Case 10)

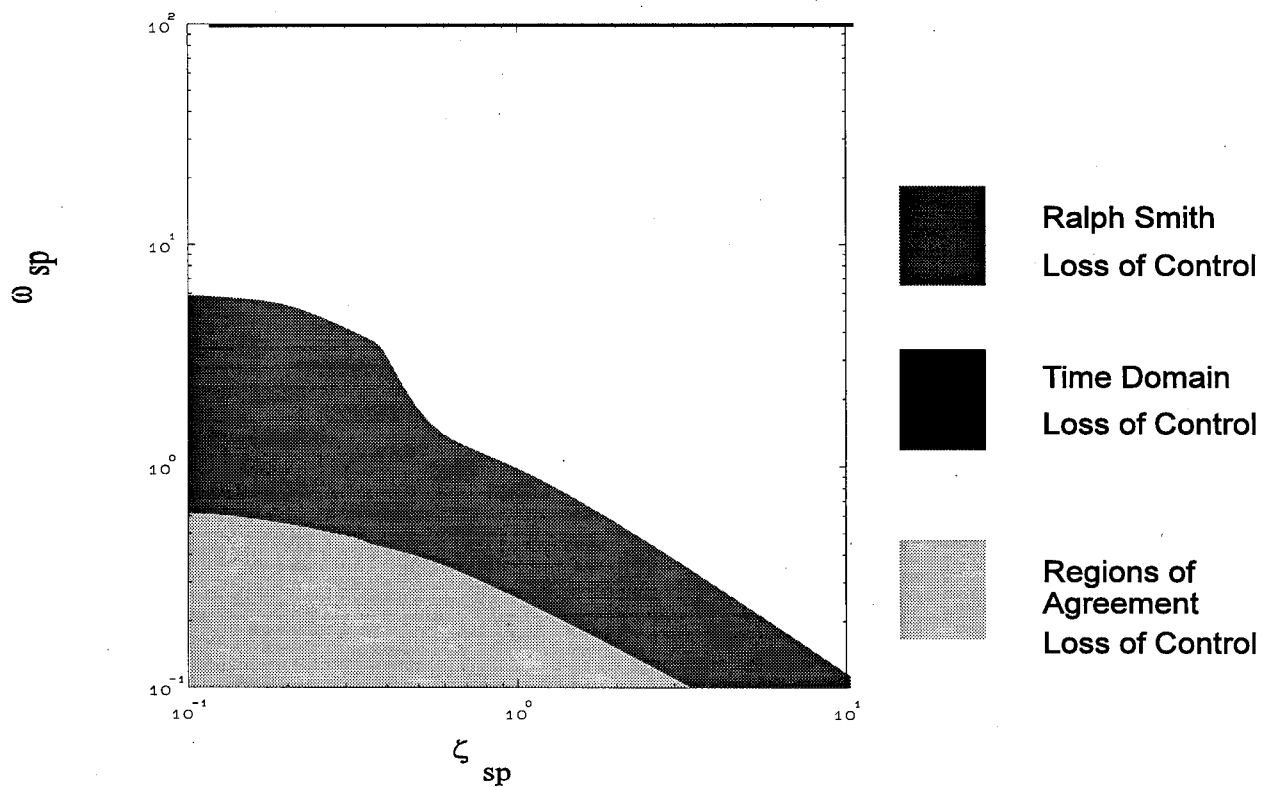


Figure C.60: Loss of Control Regions (Case 10)

C.11 Case 11

$$\frac{\theta(s)}{\delta(s)} = \frac{3.9897(1.32s + 1)e^{-.15s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

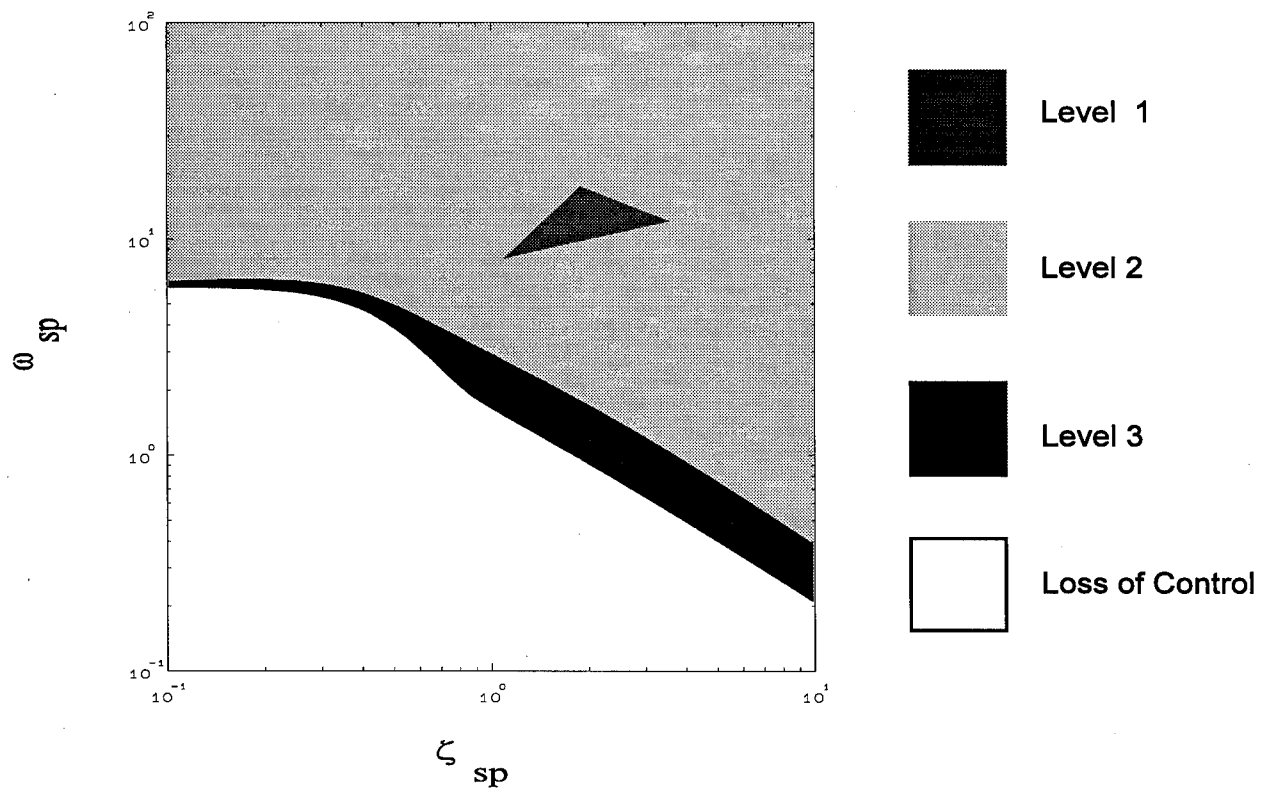


Figure C.61: Ralph Smith Criteria (Case 11)

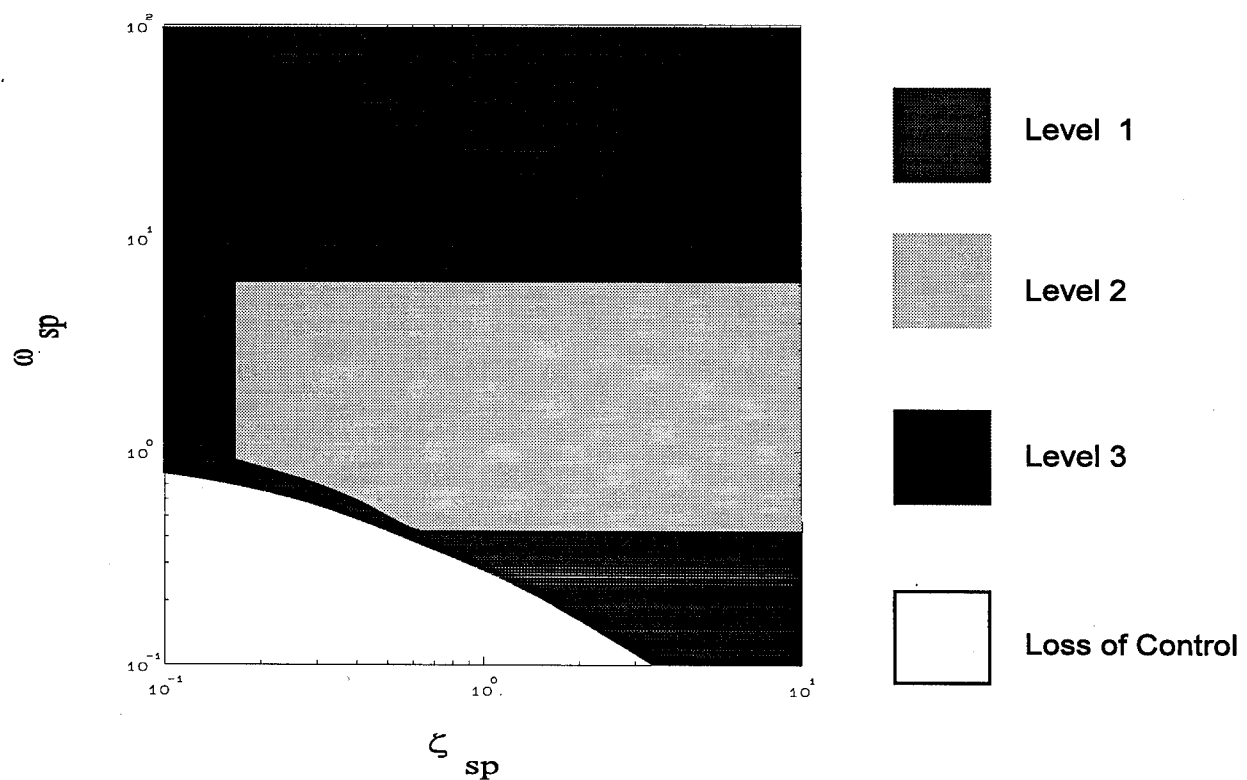


Figure C.62: Time Domain Criteria (Case 11)

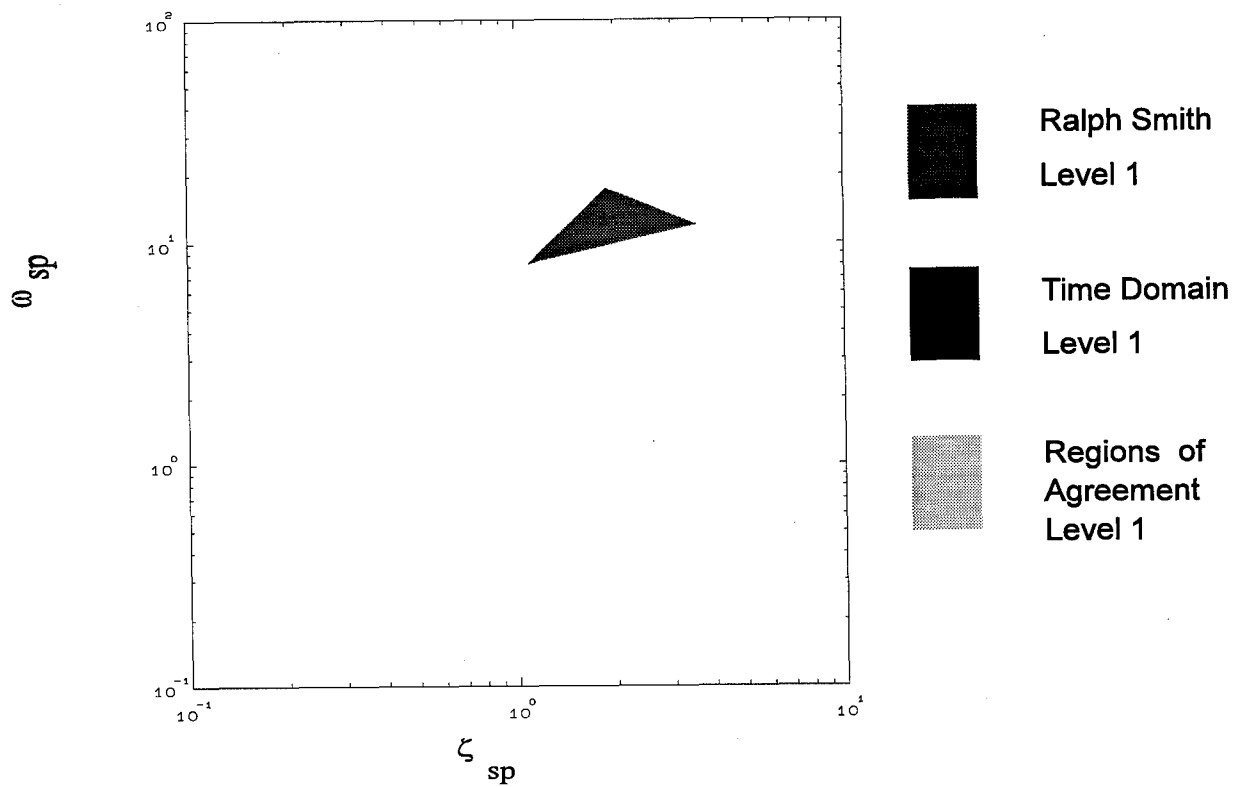


Figure C.63: Level 1 Regions (Case 11)

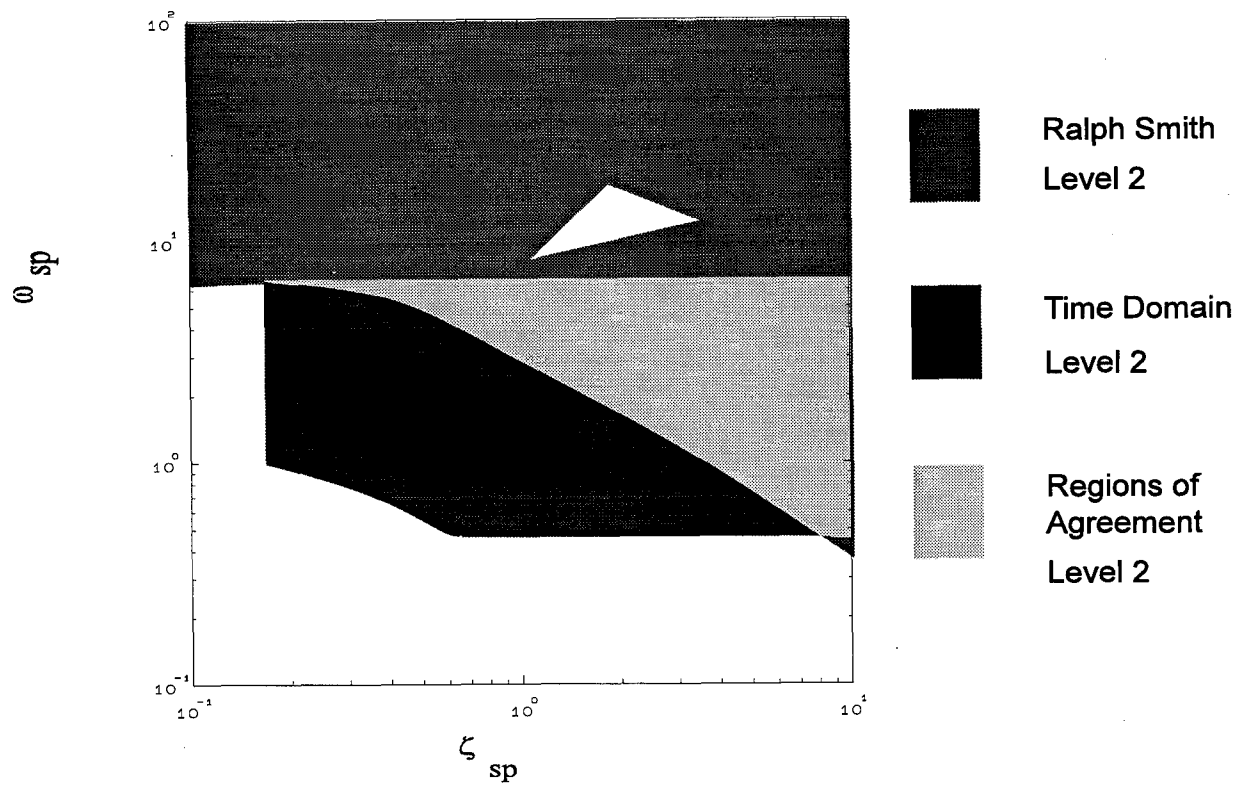


Figure C.64: Level 2 Regions (Case 11)

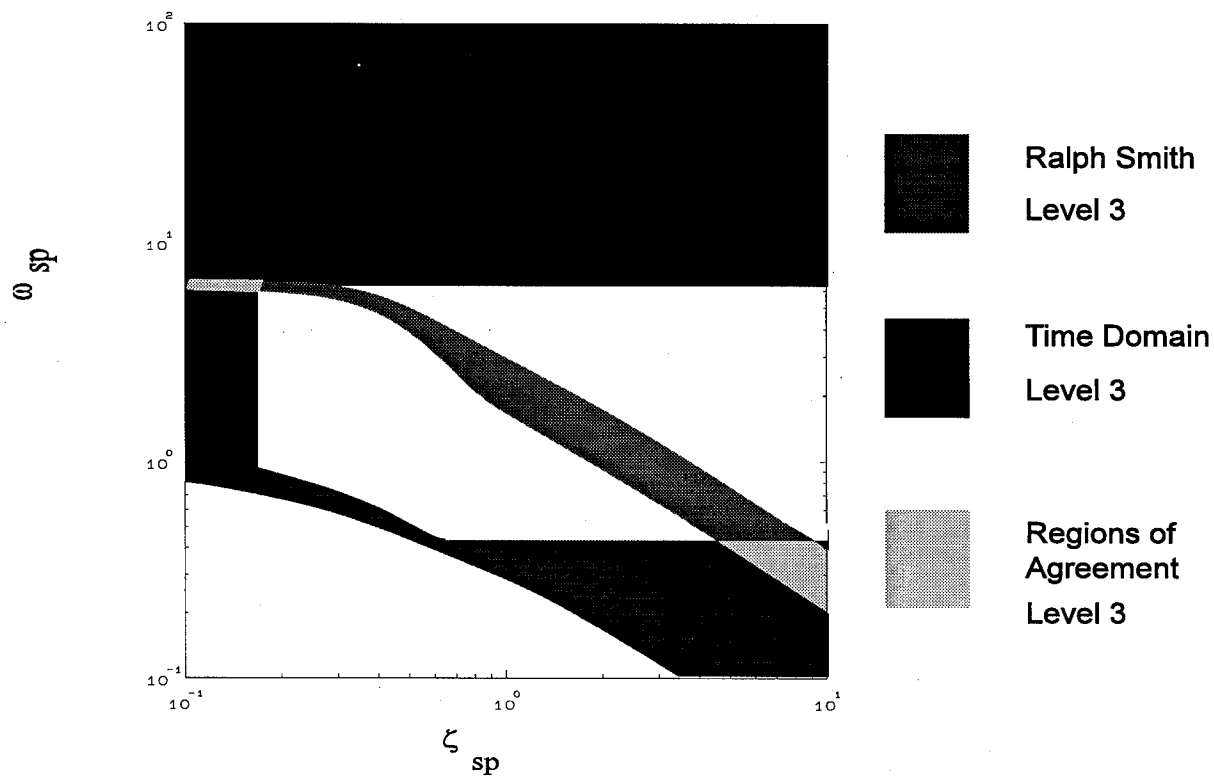


Figure C.65: Level 3 Regions (Case 11)

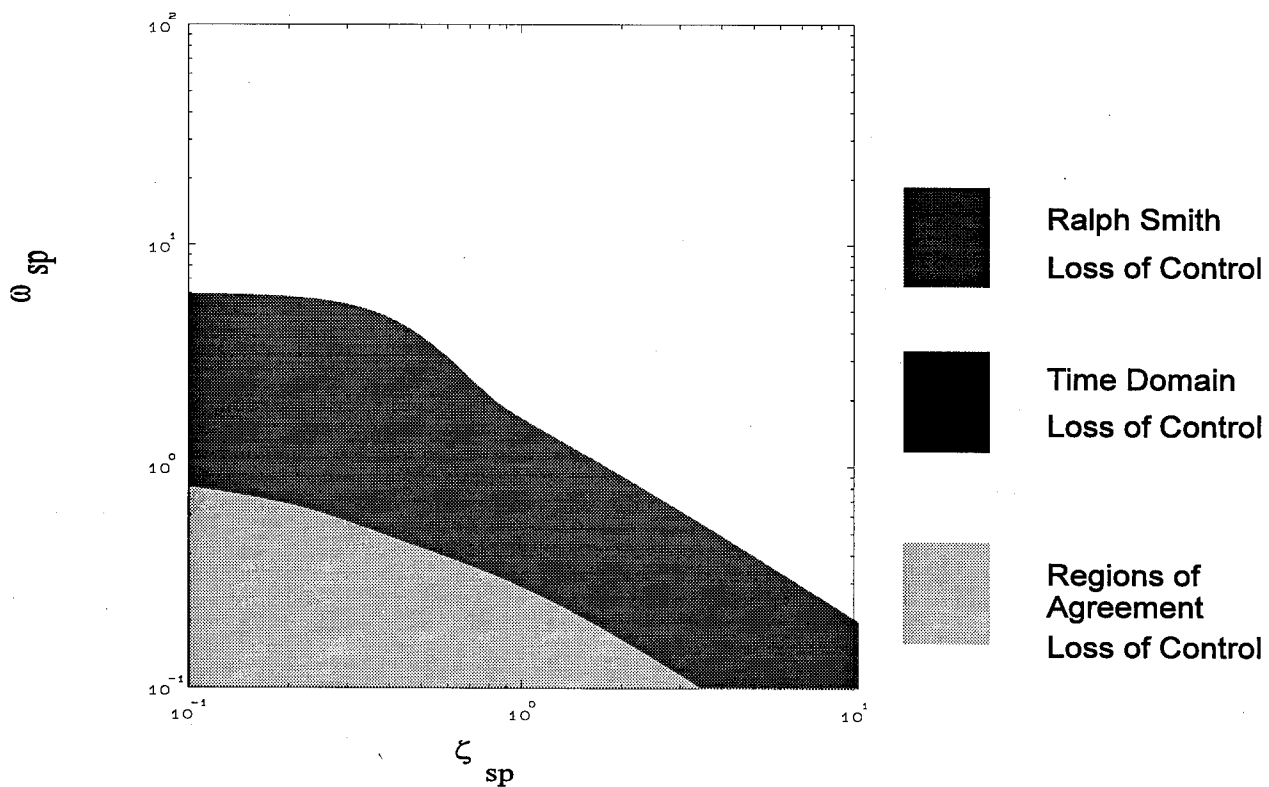


Figure C.66: Loss of Control Regions (Case 11)

C.12 Case 12

$$\frac{\theta(s)}{\delta(s)} = \frac{3.9897(1.32s + 1)e^{-.2s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

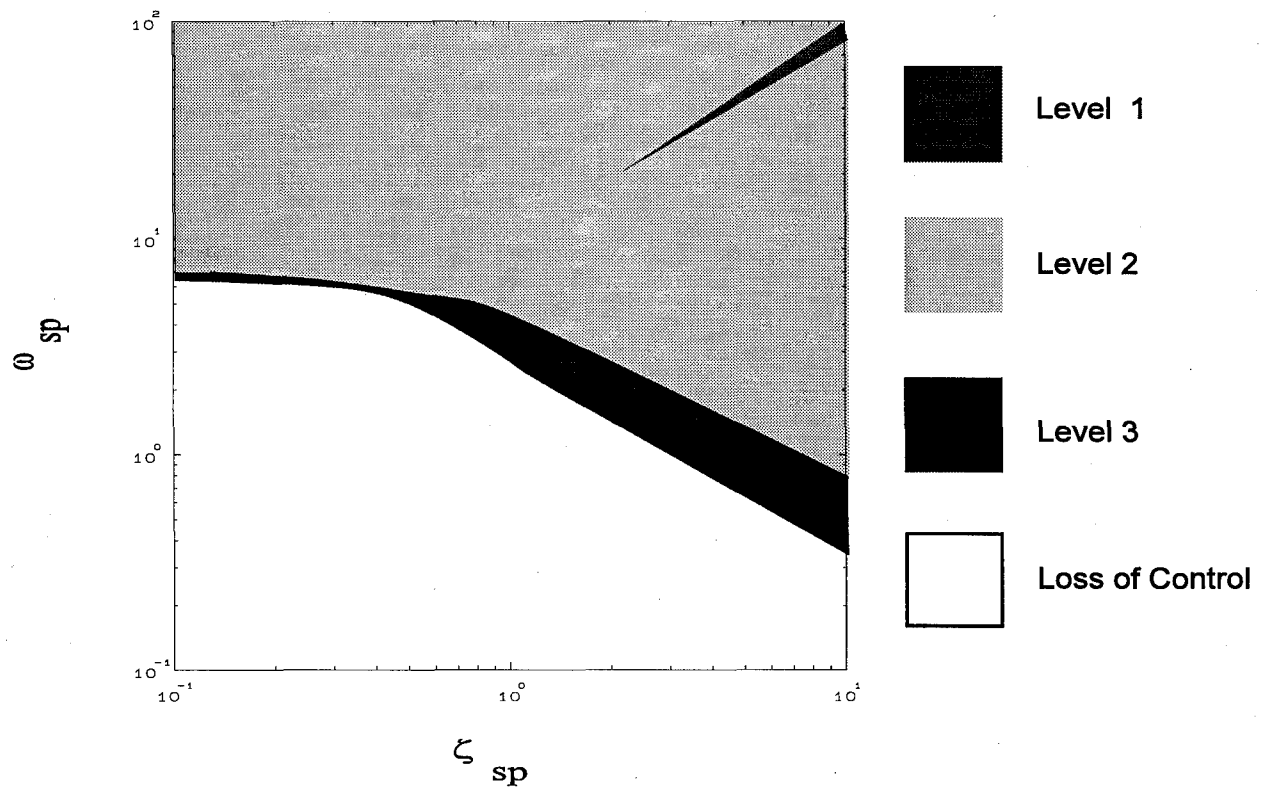


Figure C.67: Ralph Smith Criteria (Case 12)

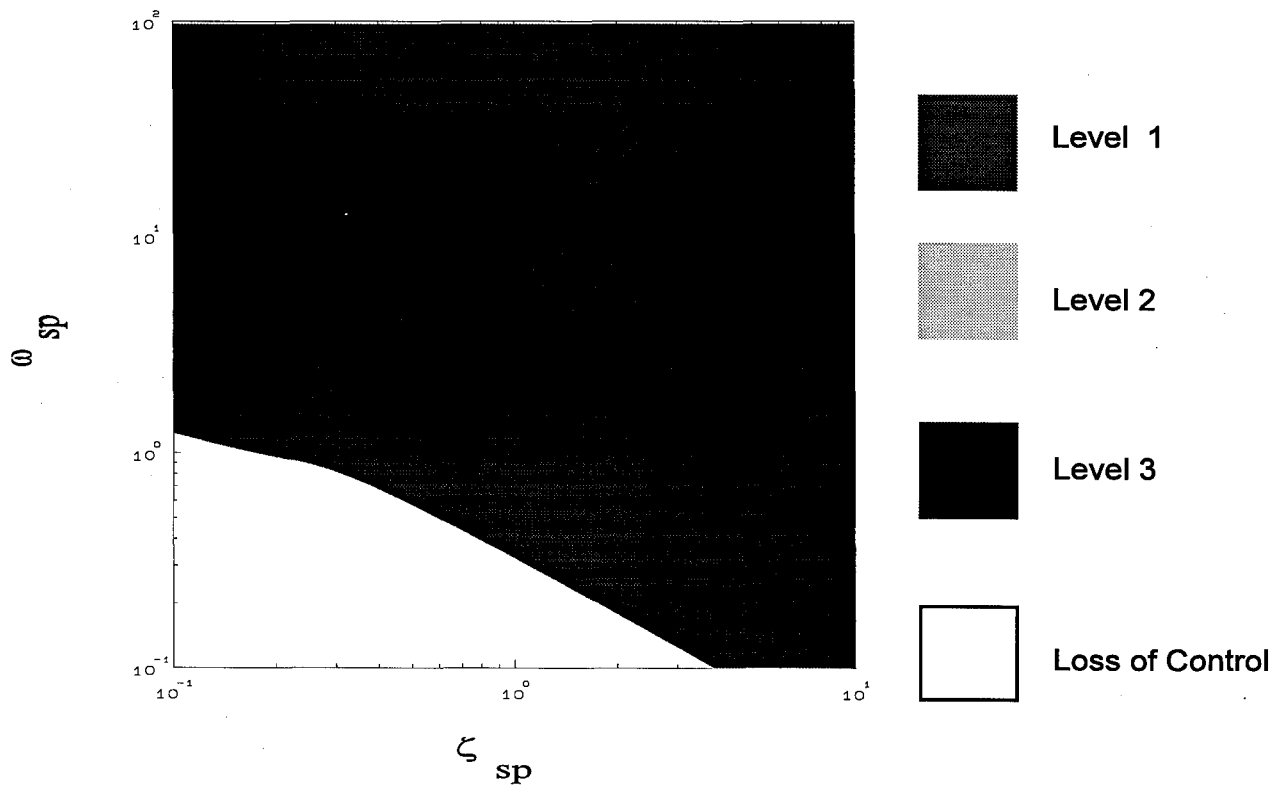


Figure C.68: Time Domain Criteria (Case 12)

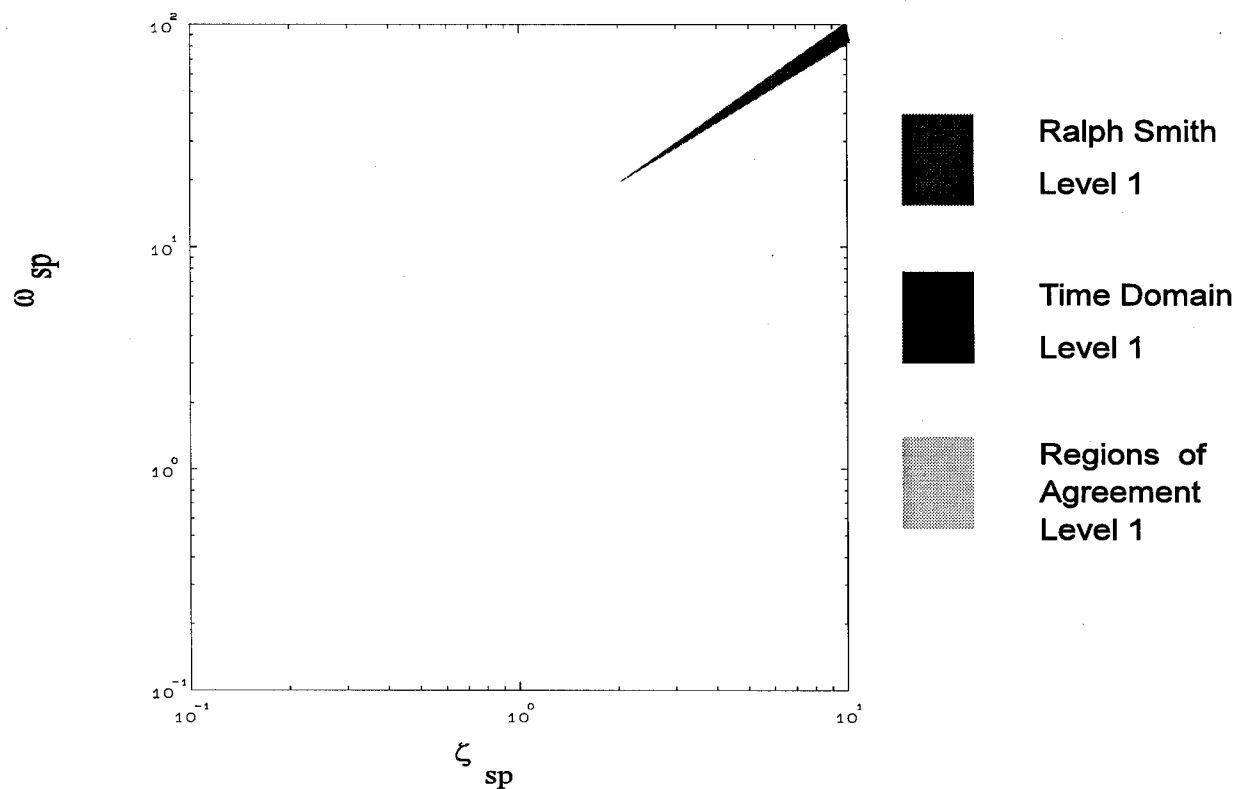


Figure C.69: Level 1 Regions (Case 12)

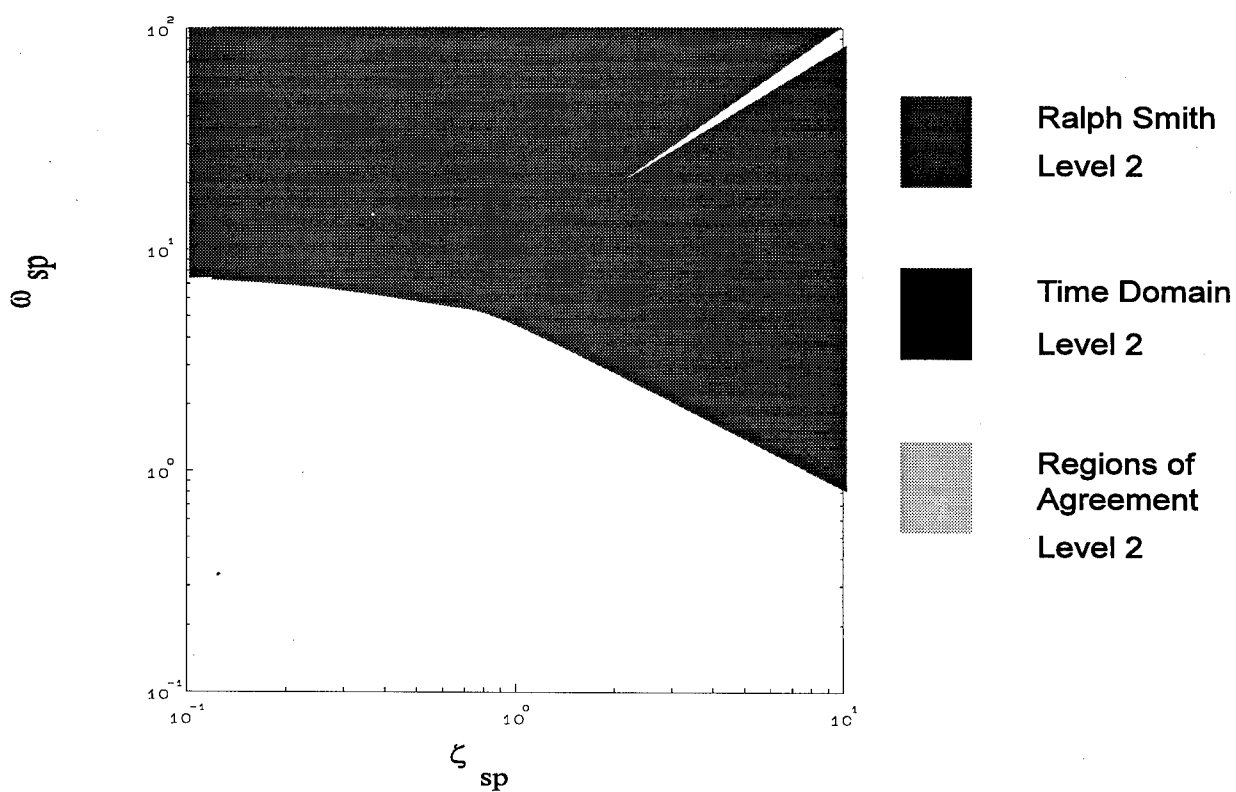


Figure C.70: Level 2 Regions (Case 12)

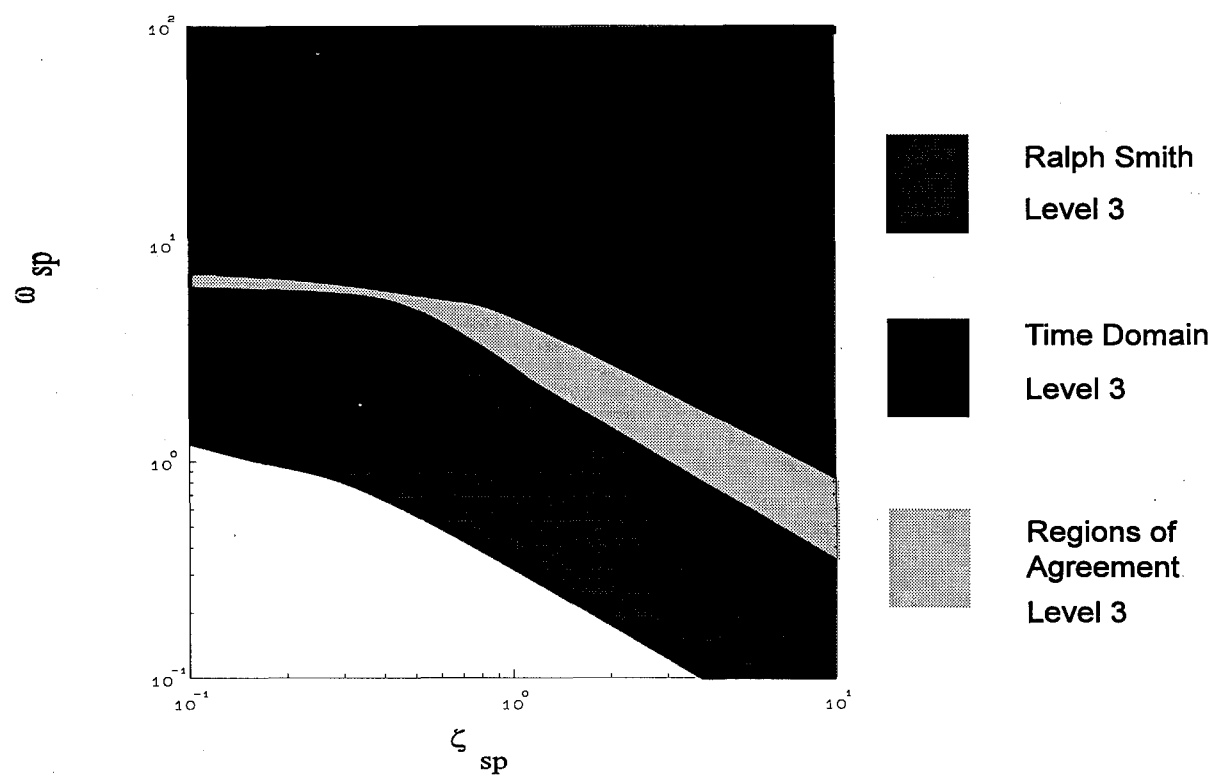


Figure C.71: Level 3 Regions (Case 12)

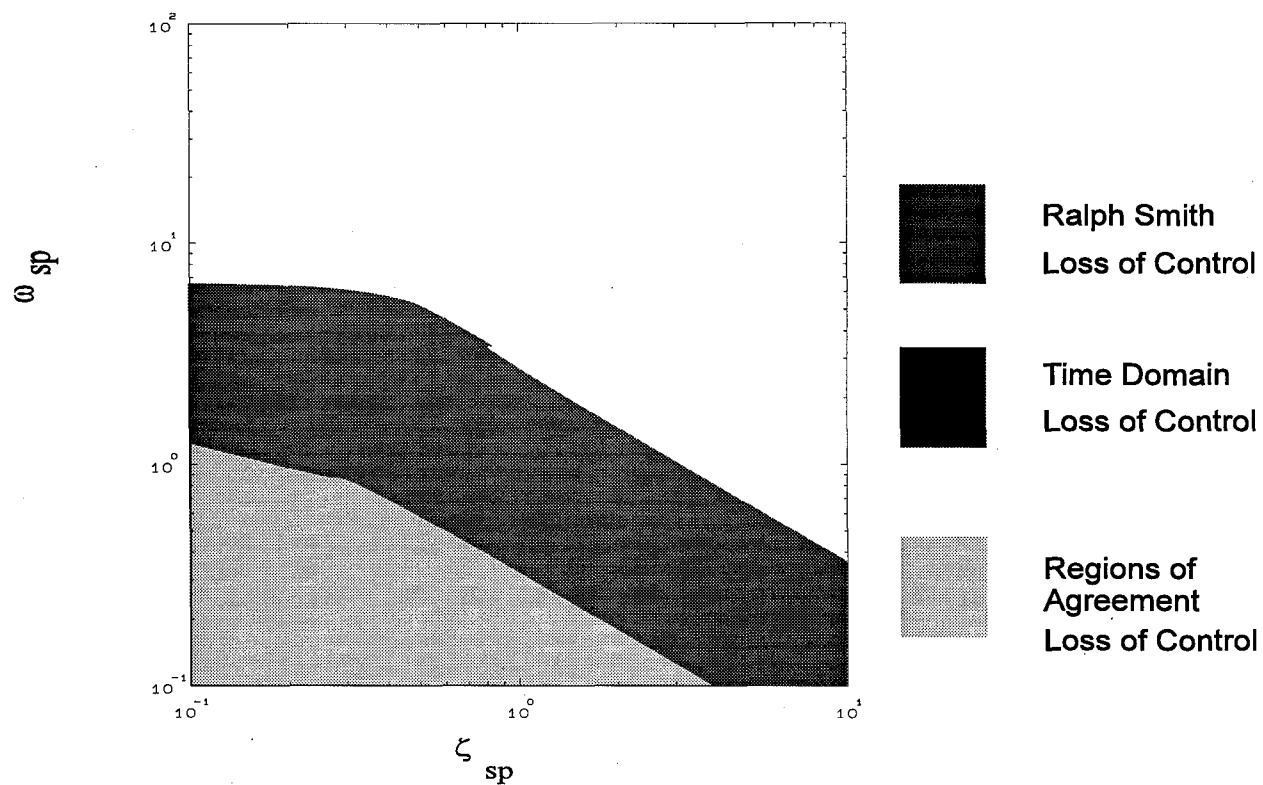


Figure C.72: Loss of Control Regions (Case 12)

C.13 Case 13

F-16 Transfer Function I

$$\frac{\theta(s)}{\delta(s)} = \frac{.237(2.12s + 1)e^{0s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

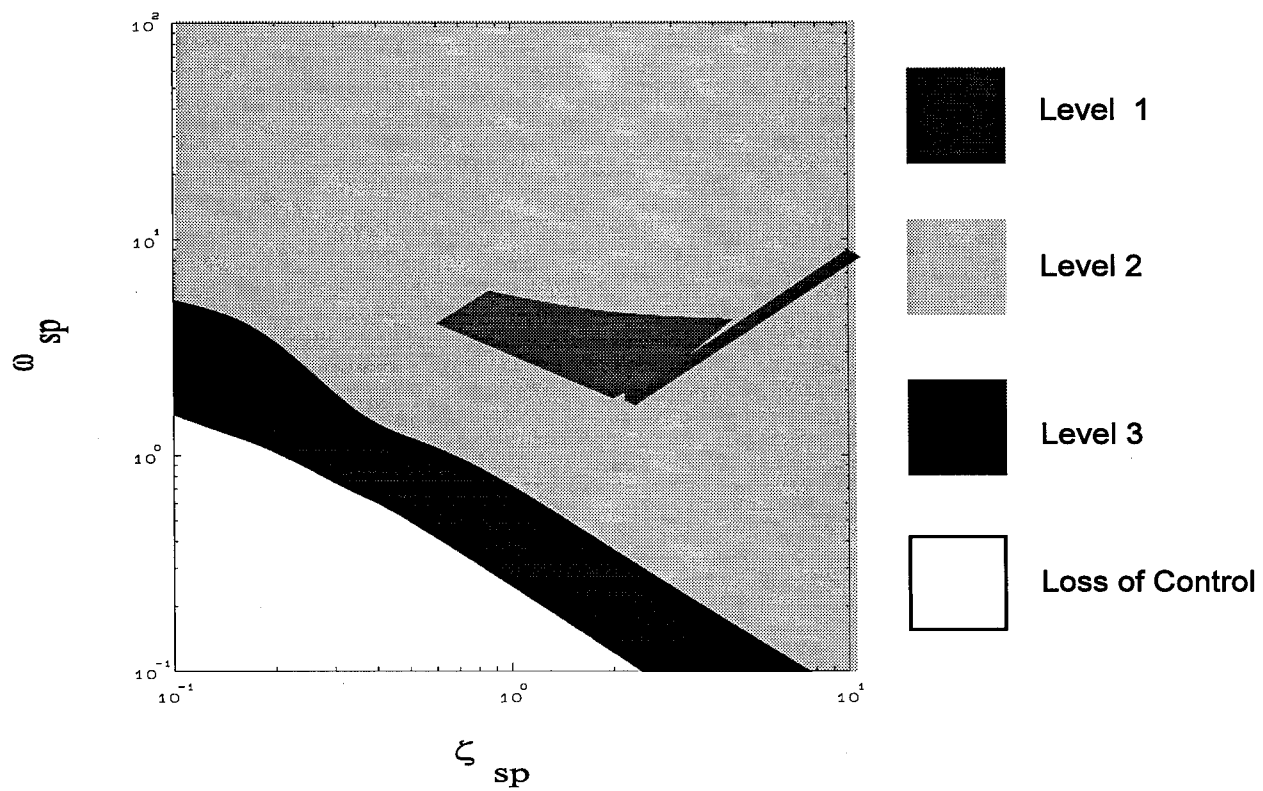


Figure C.73: Ralph Smith Criteria (Case 13)

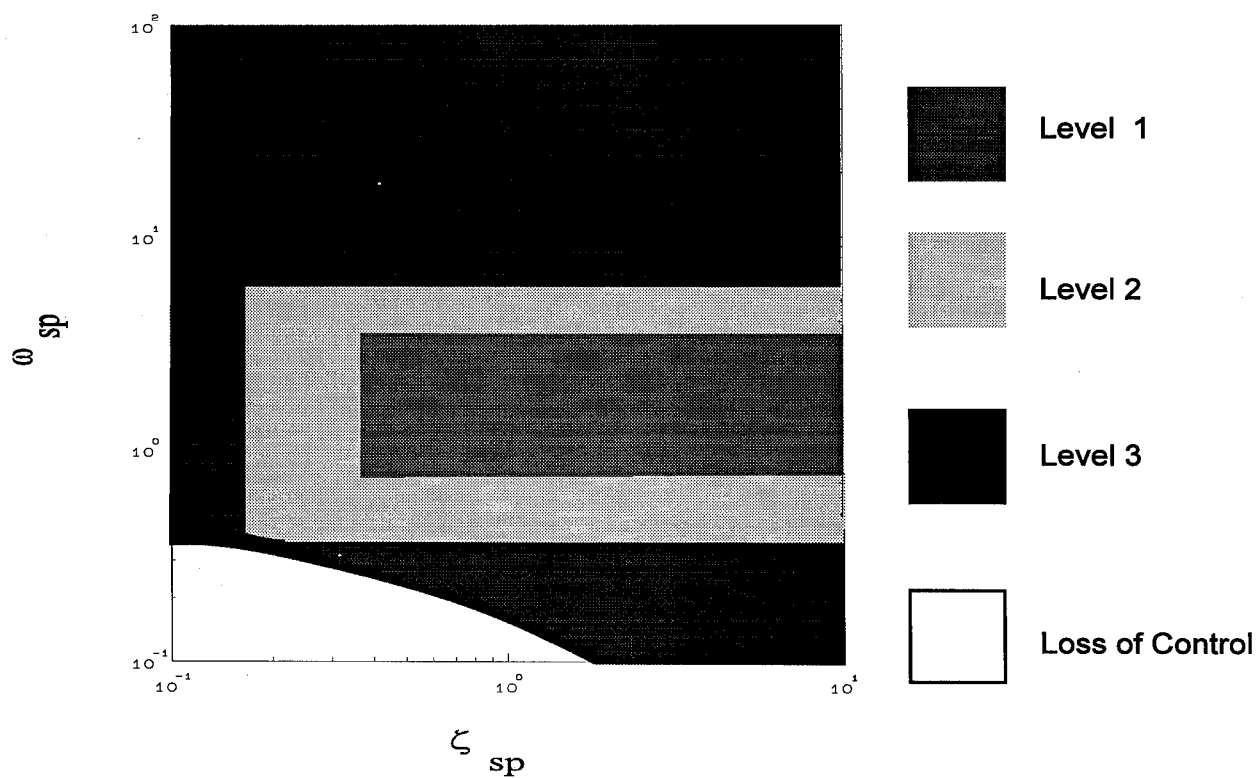


Figure C.74: Time Domain Criteria (Case 13)

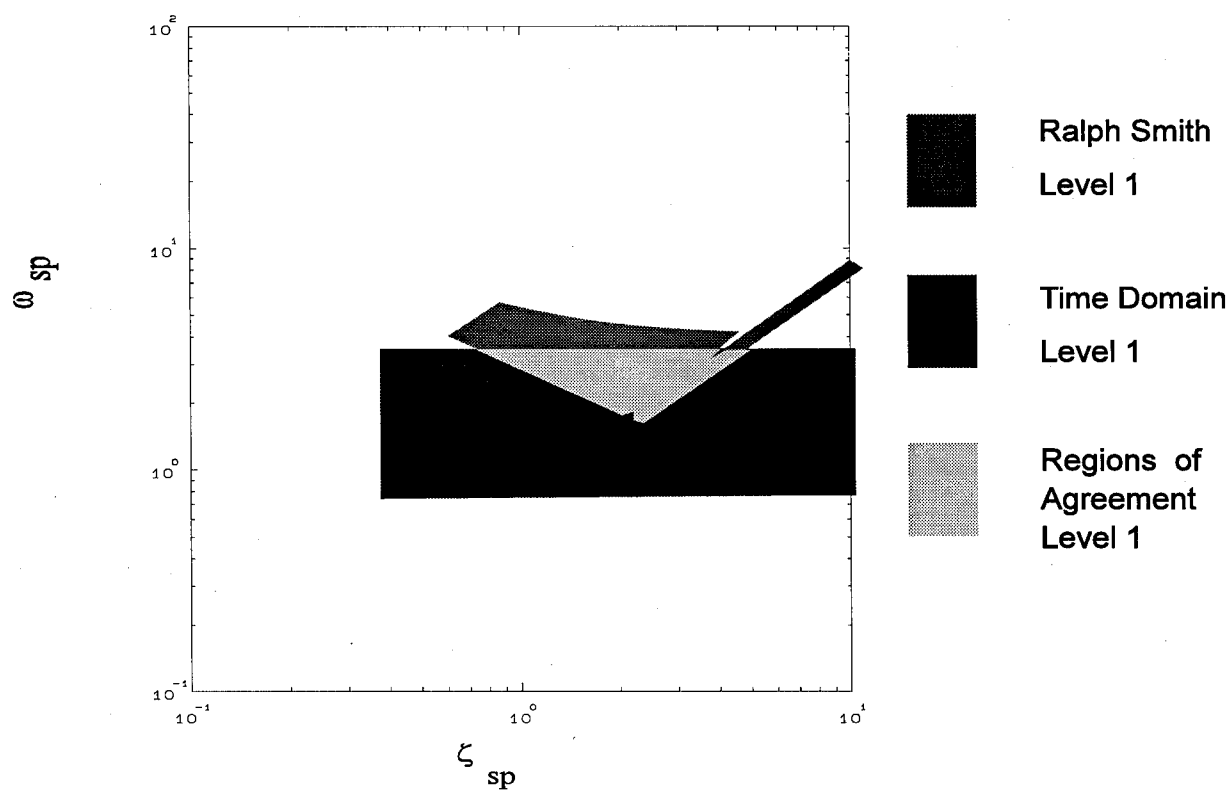


Figure C.75: Level 1 Regions (Case 13)

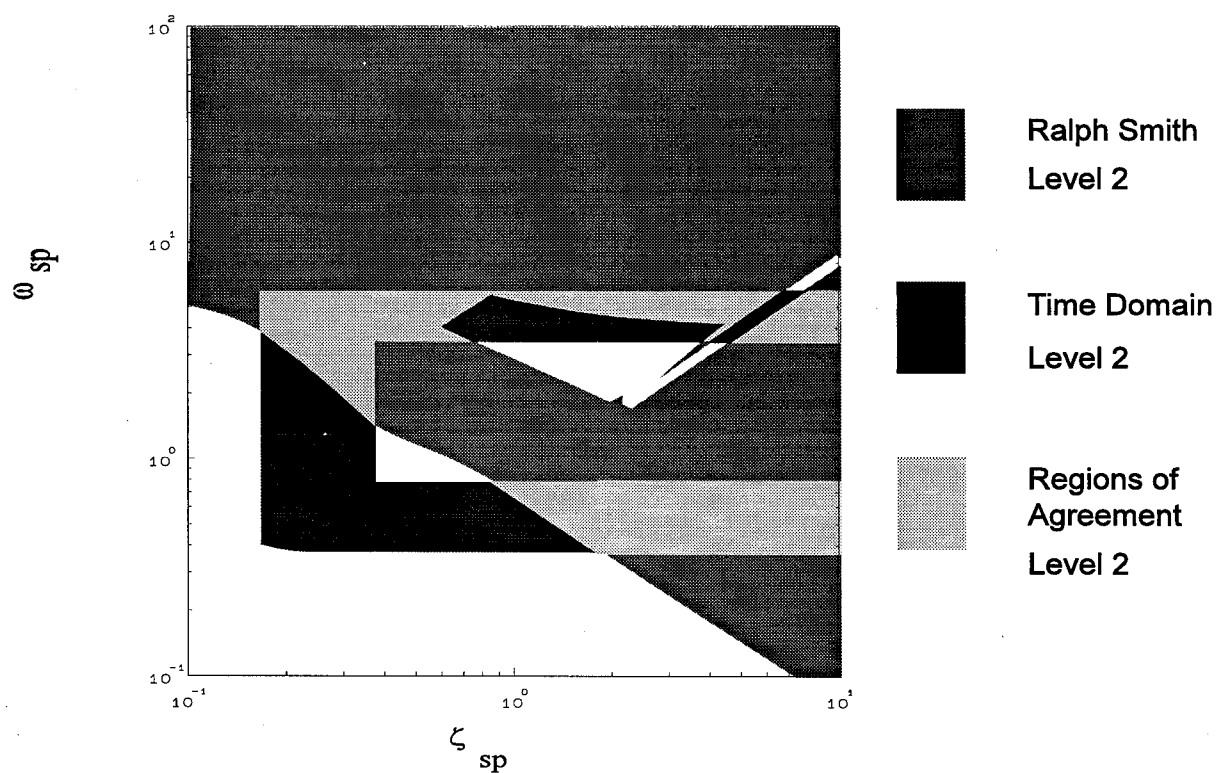


Figure C.76: Level 2 Regions (Case 13)

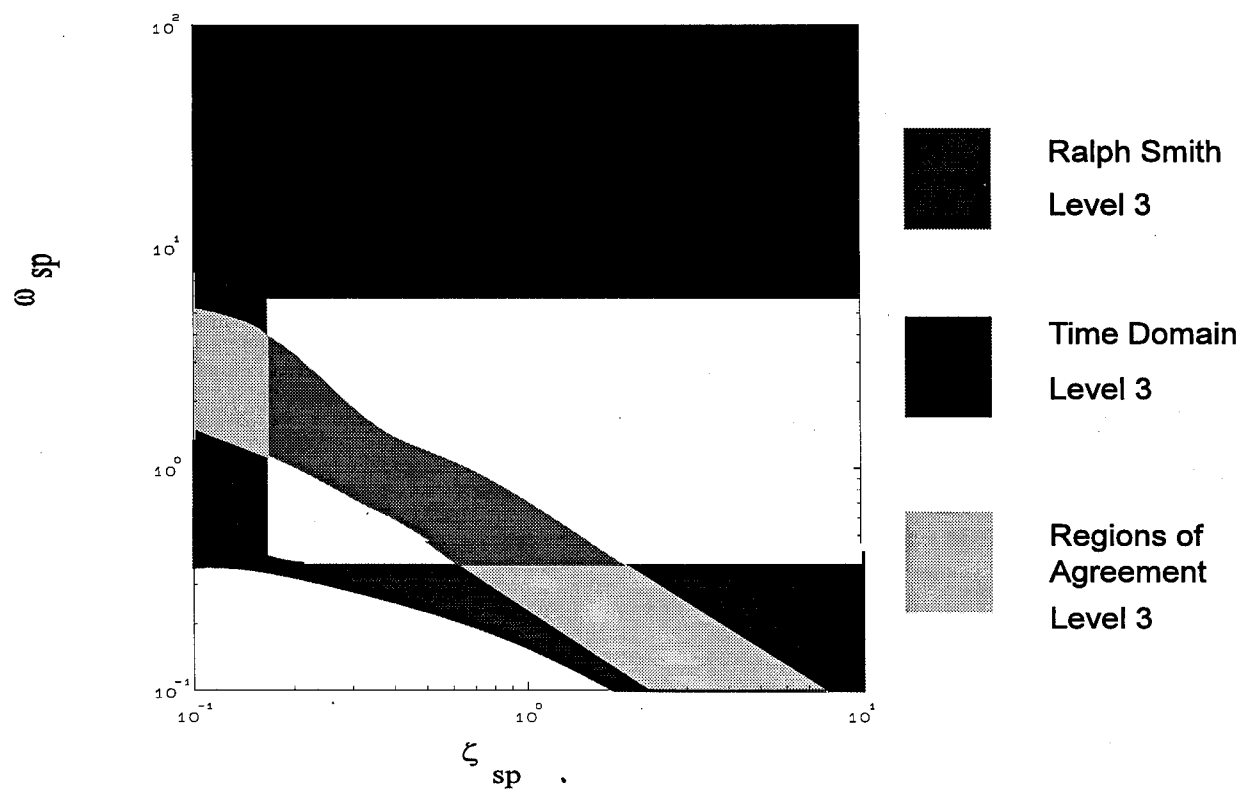


Figure C.77: Level 3 Regions (Case 13)

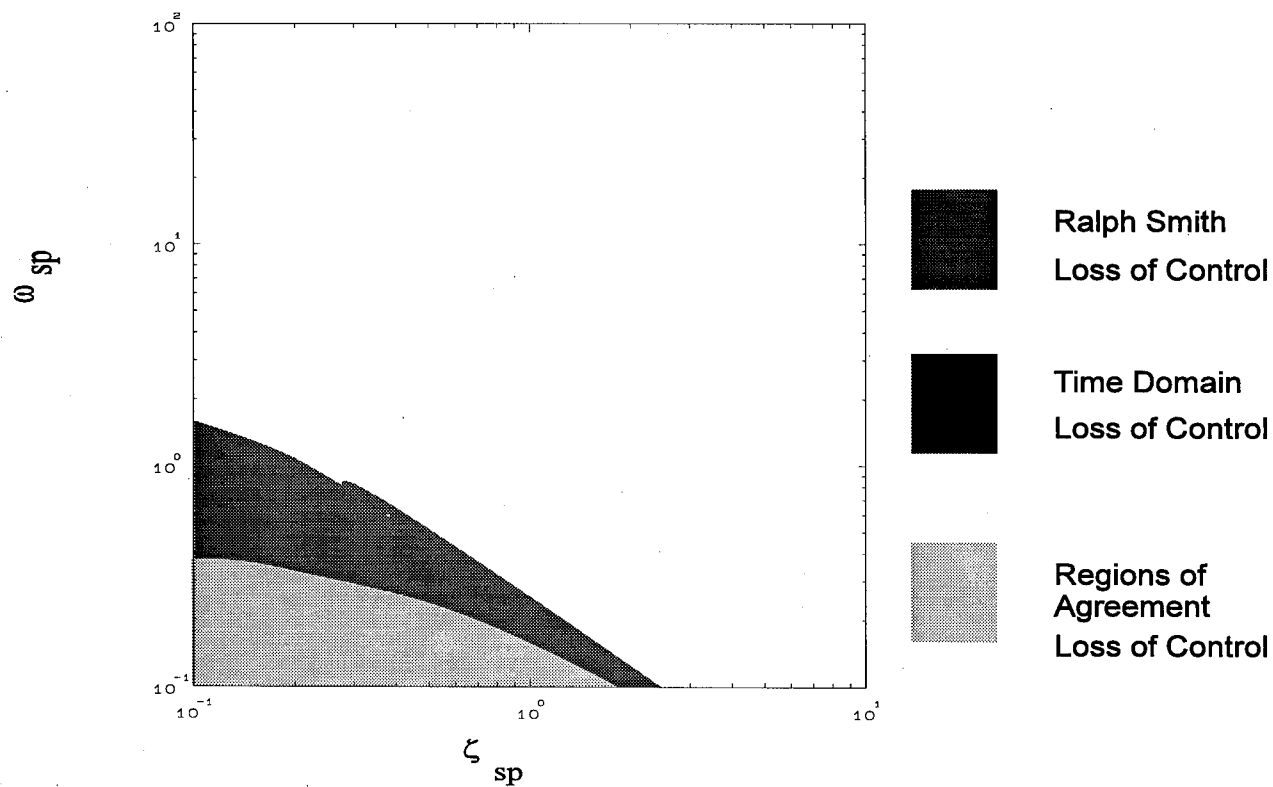


Figure C.78: Loss of Control Region (Case 13)

C.14 Case 14

$$\frac{\theta(s)}{\delta(s)} = \frac{.237(2.12s + 1)e^{-.1s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

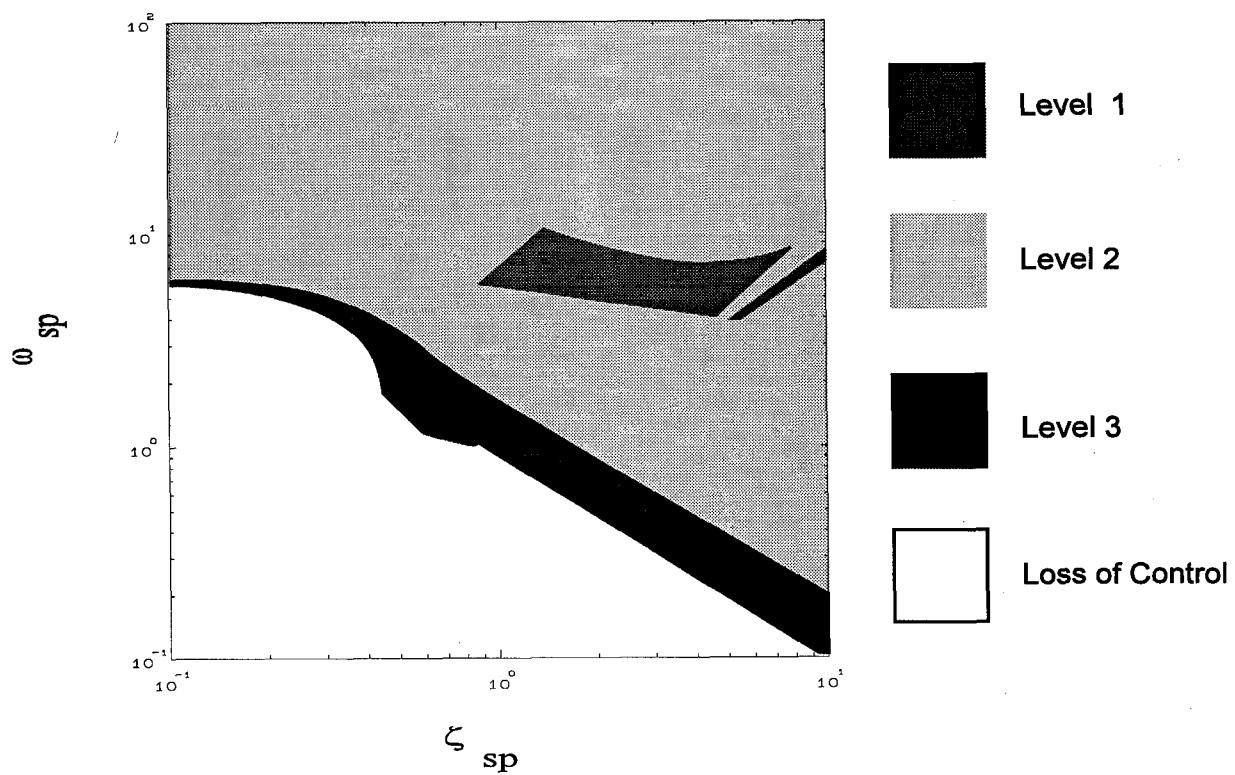


Figure C.79: Ralph Smith Criteria (Case 14)

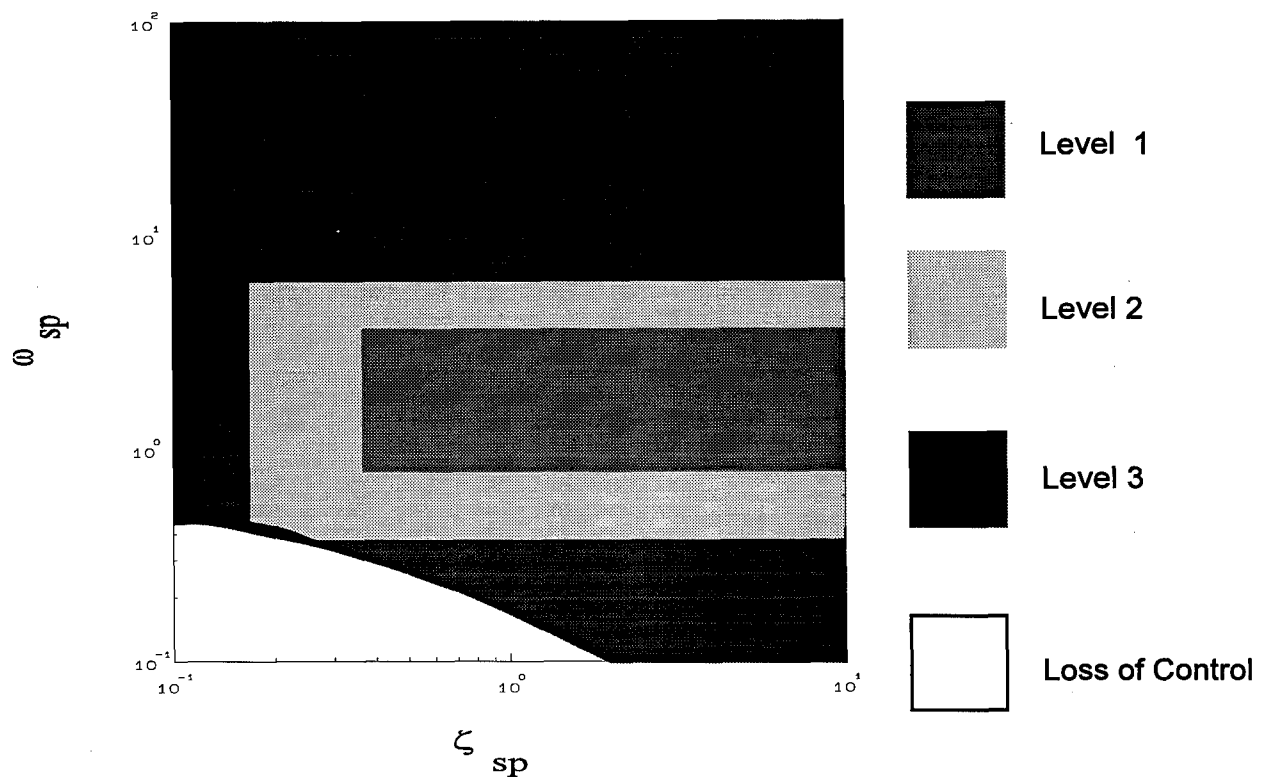


Figure C.80: Time Domain Criteria (Case 14)

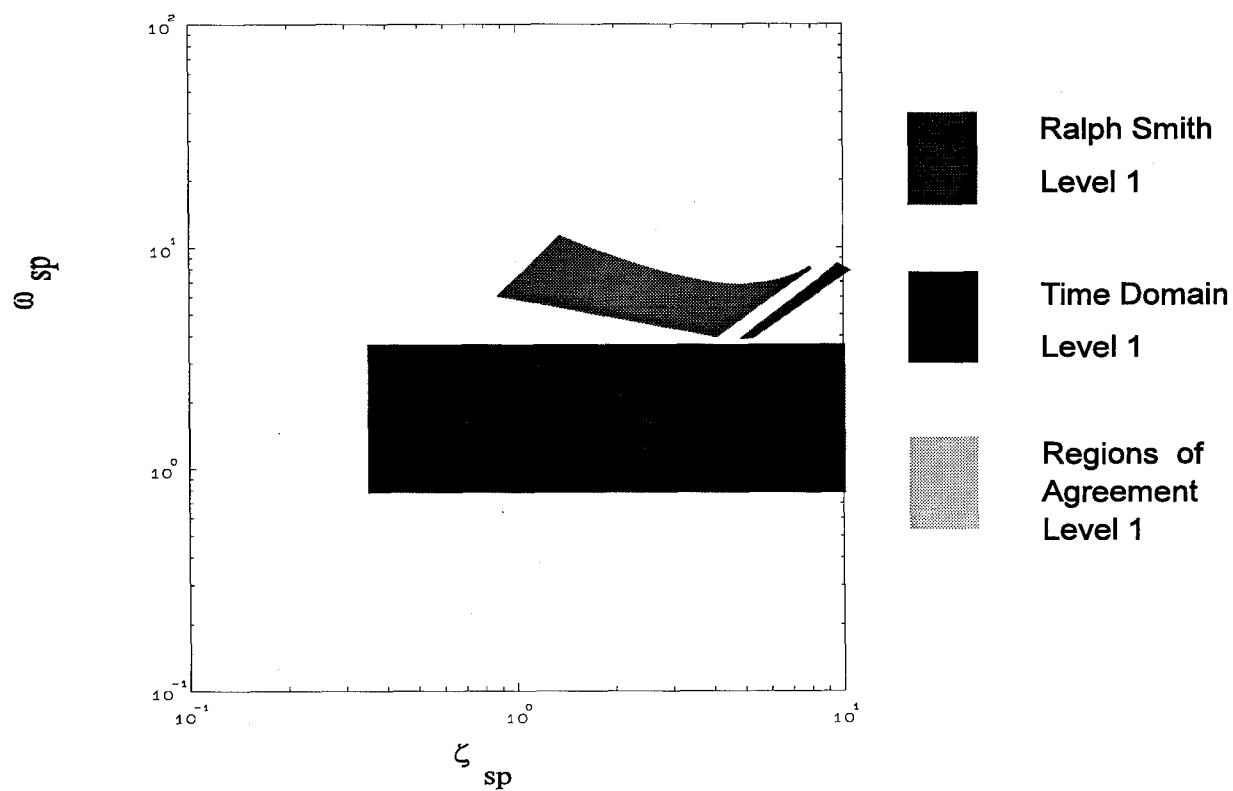


Figure C.81: Level 1 Regions (Case 14)

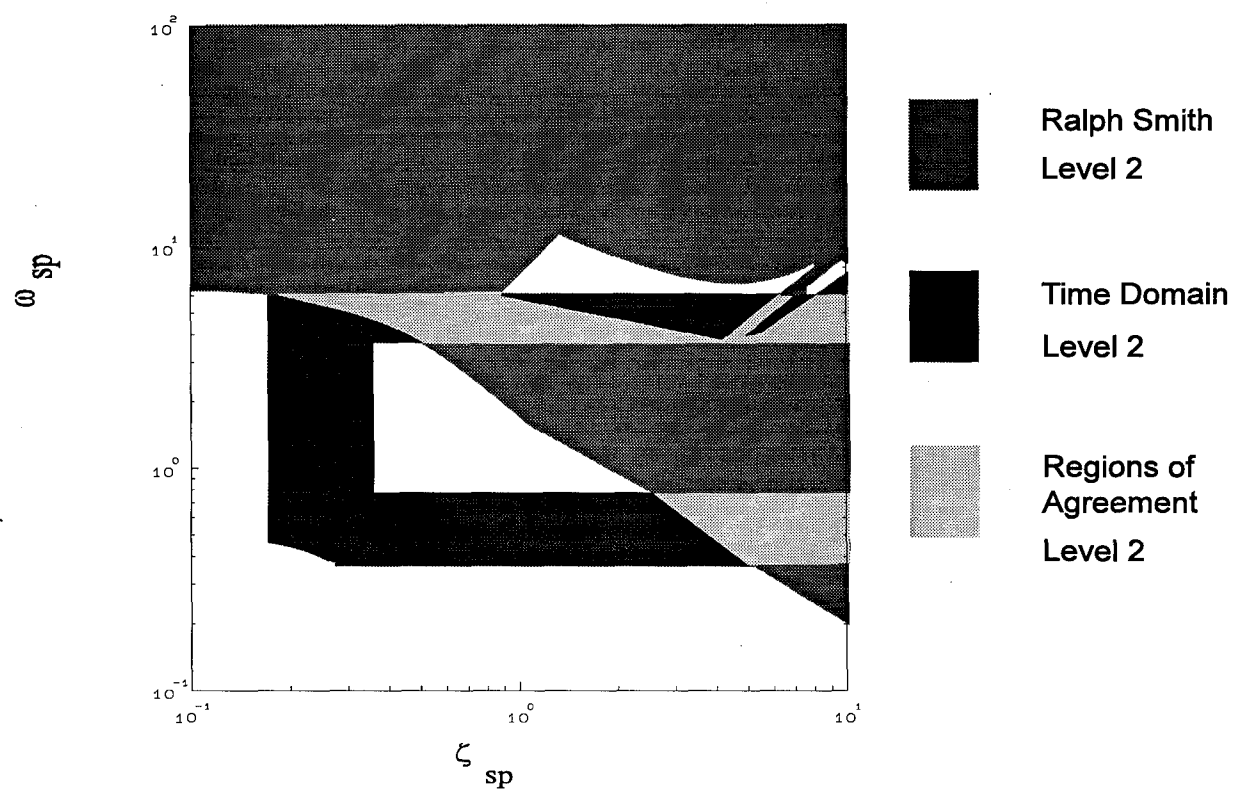


Figure C.82: Level 2 Regions (Case 14)

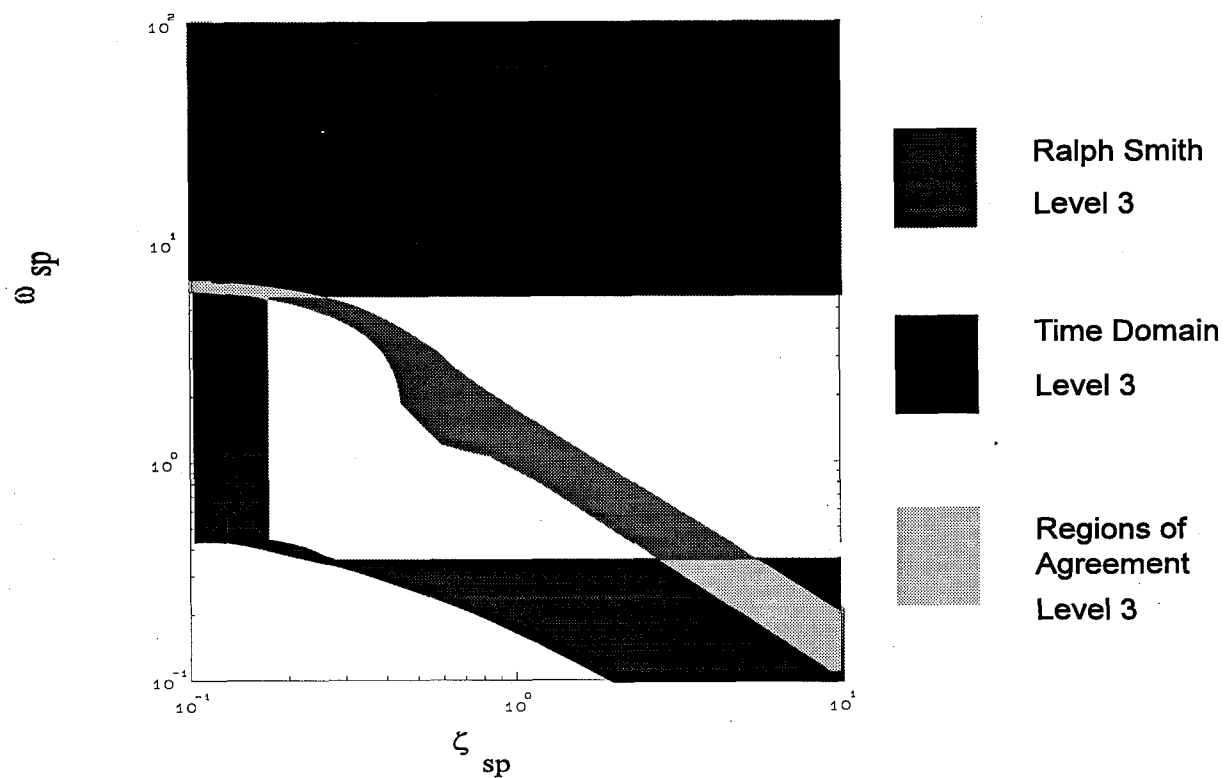


Figure C.83: Level 3 Regions (Case 14)

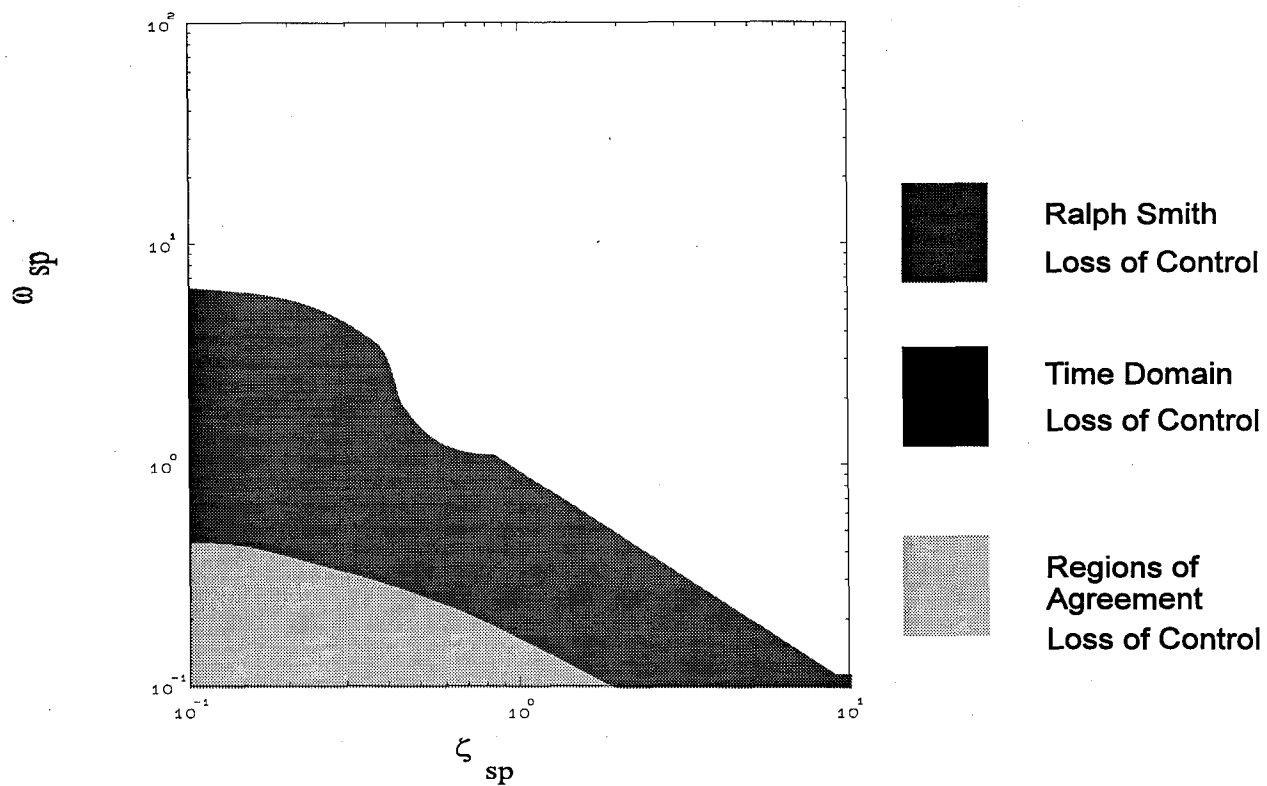


Figure C.84: Loss of Control Regions (Case 14)

C.15 Case 15

$$\frac{\theta(s)}{\delta(s)} = \frac{.237(2.12s + 1)e^{-.15s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

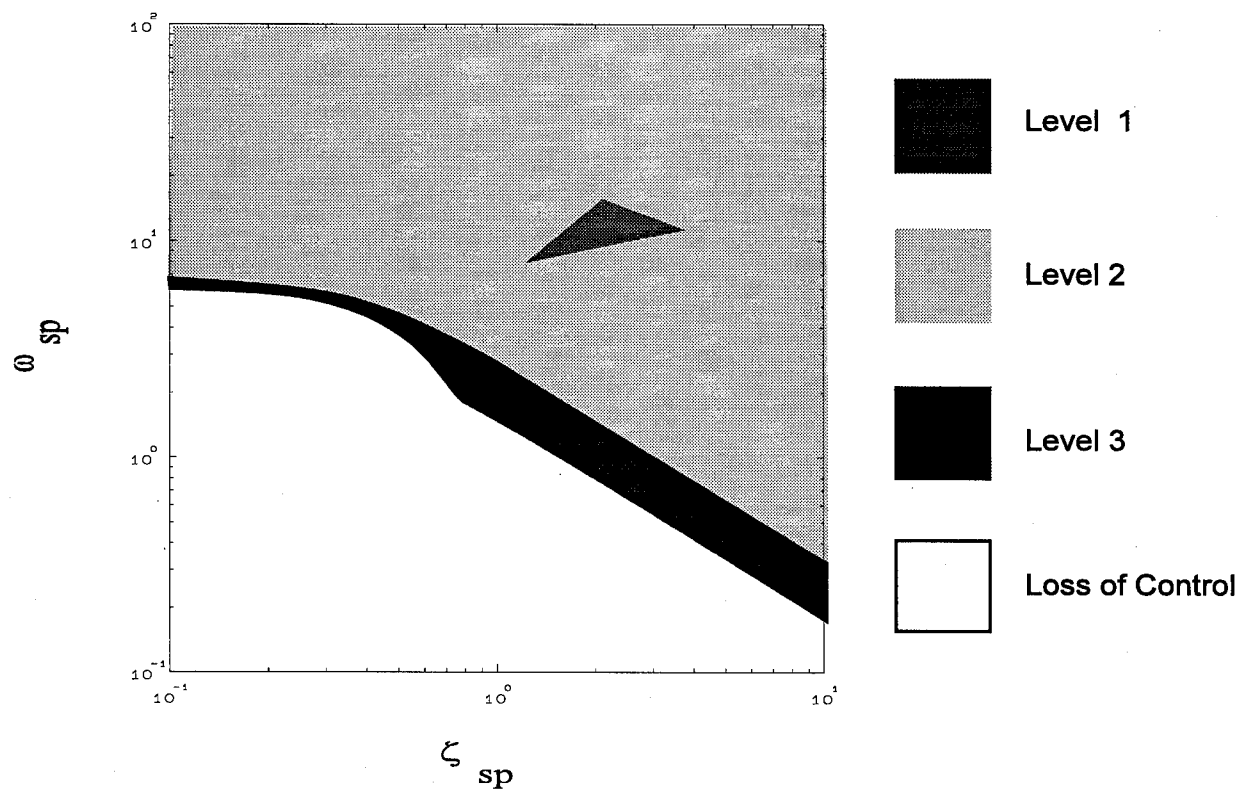


Figure C.85: Ralph Smith Criteria (Case 15)

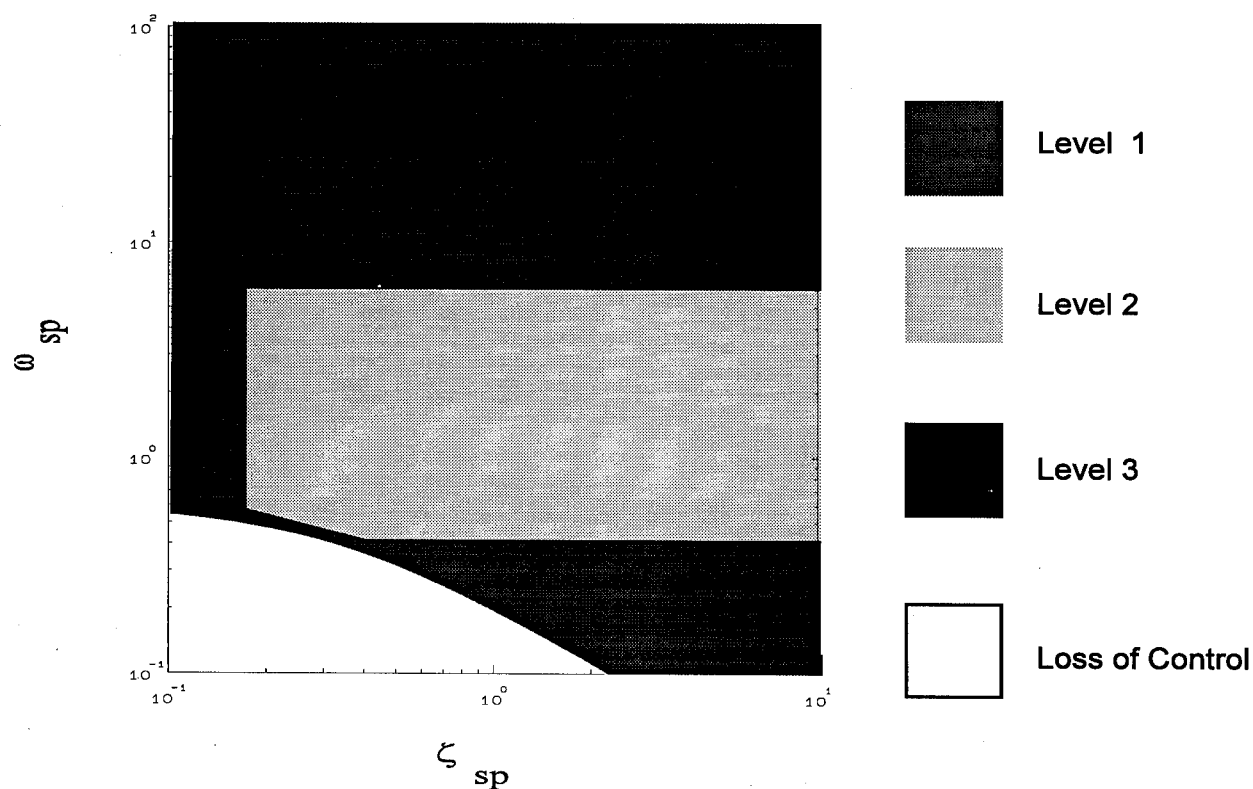


Figure C.86: Time Domain Criteria (Case 15)

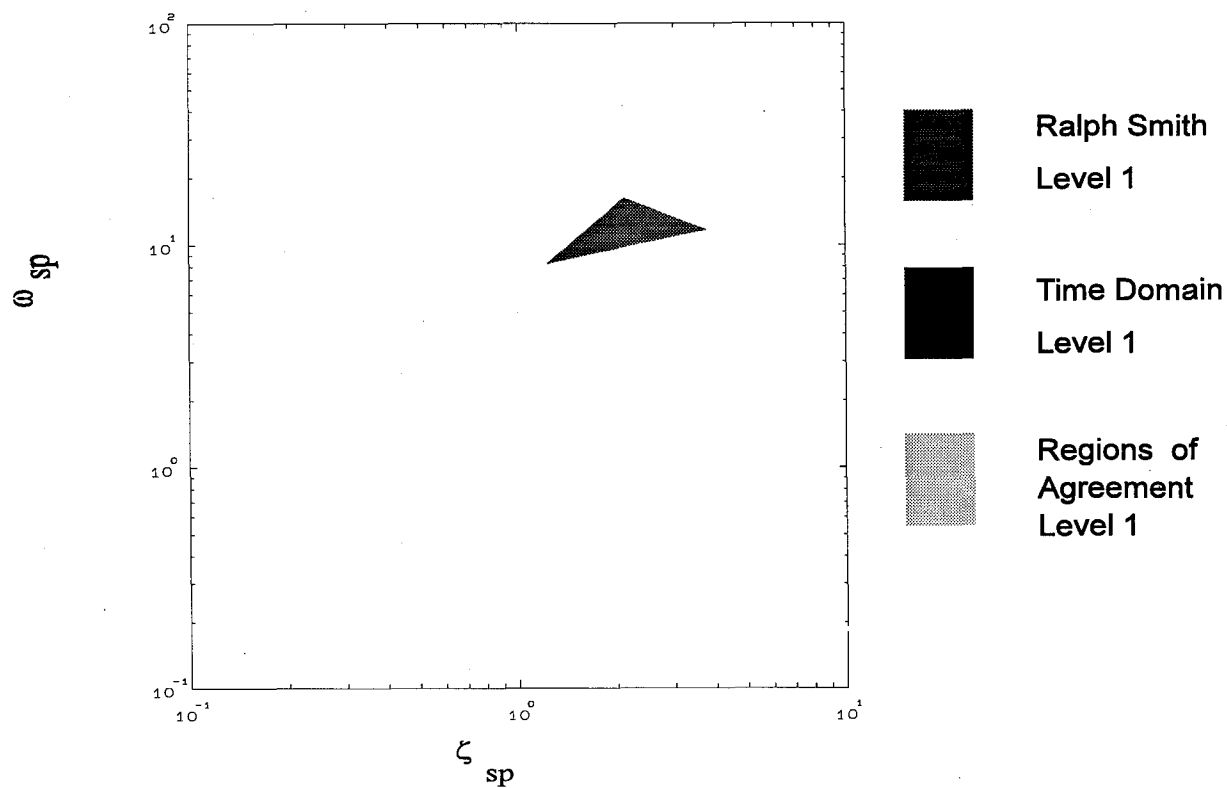


Figure C.87: Level 1 Regions (Case 15)

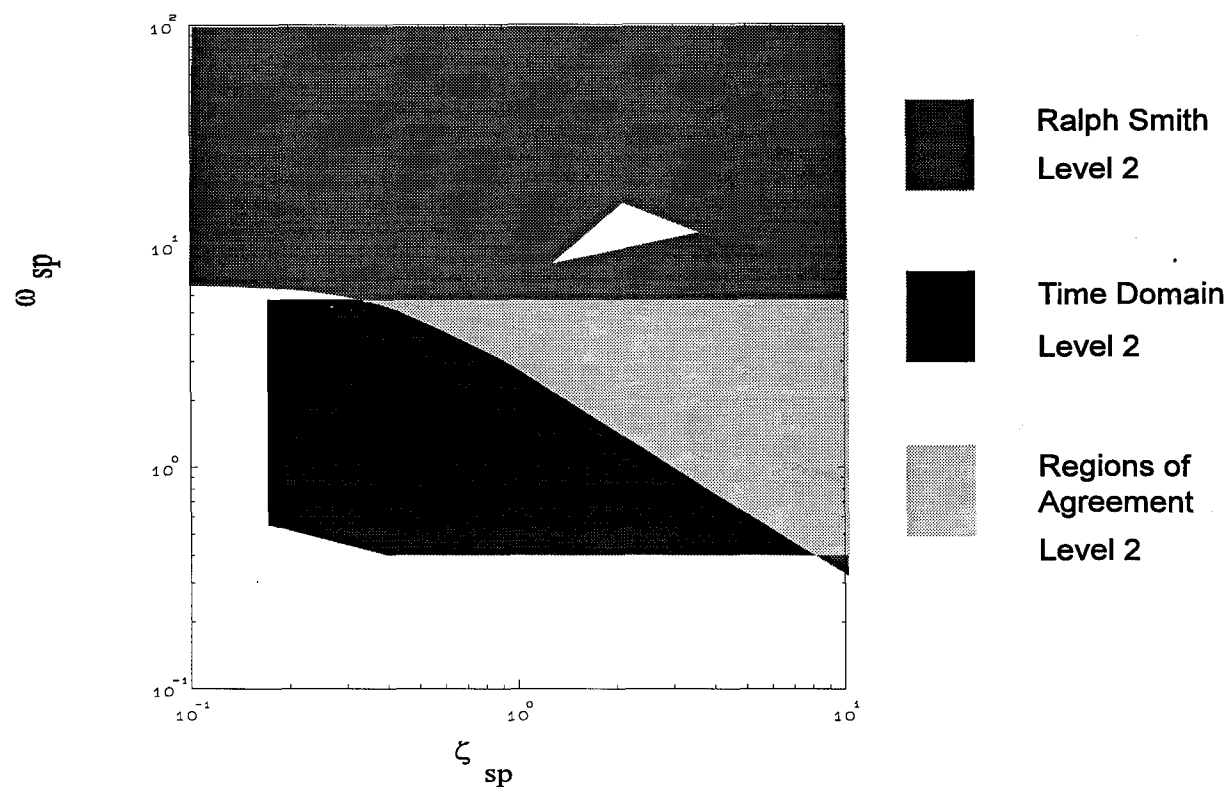


Figure C.88: Level 2 Regions (Case 15)

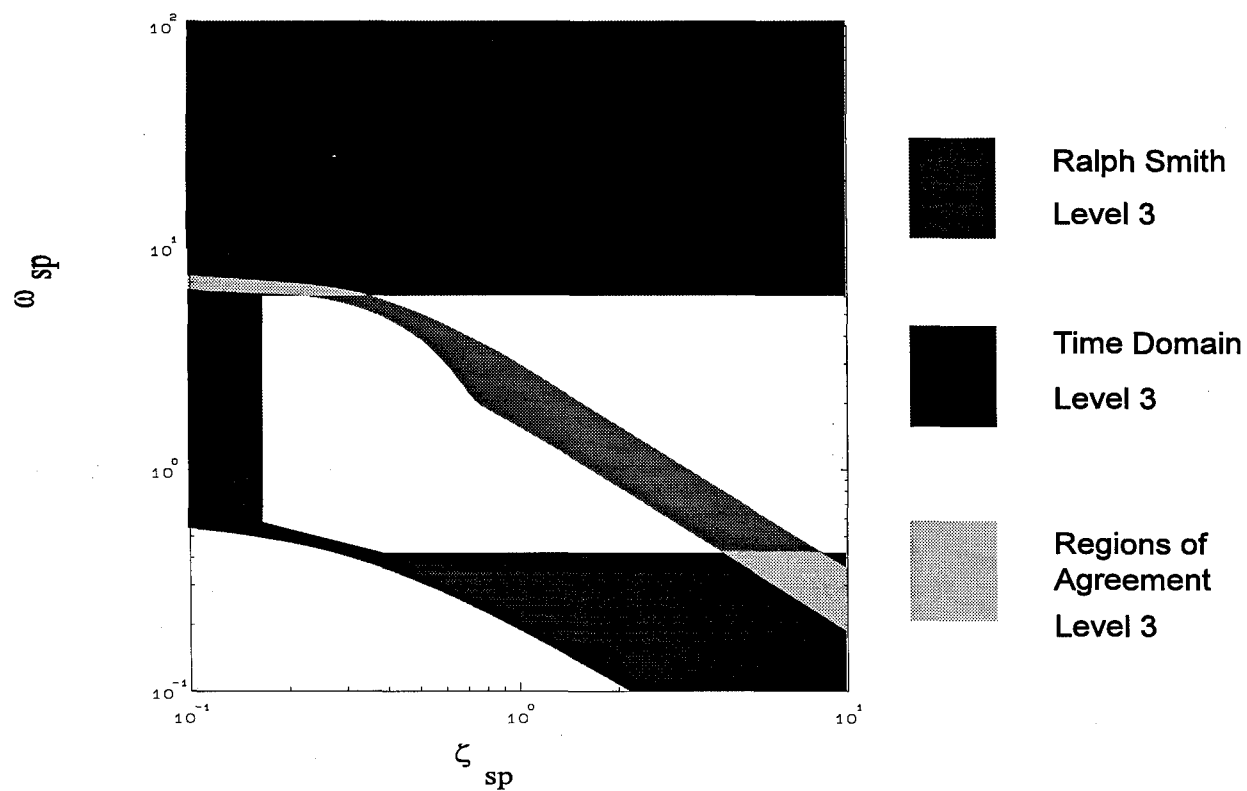


Figure C.89: Level 3 Regions (Case 15)

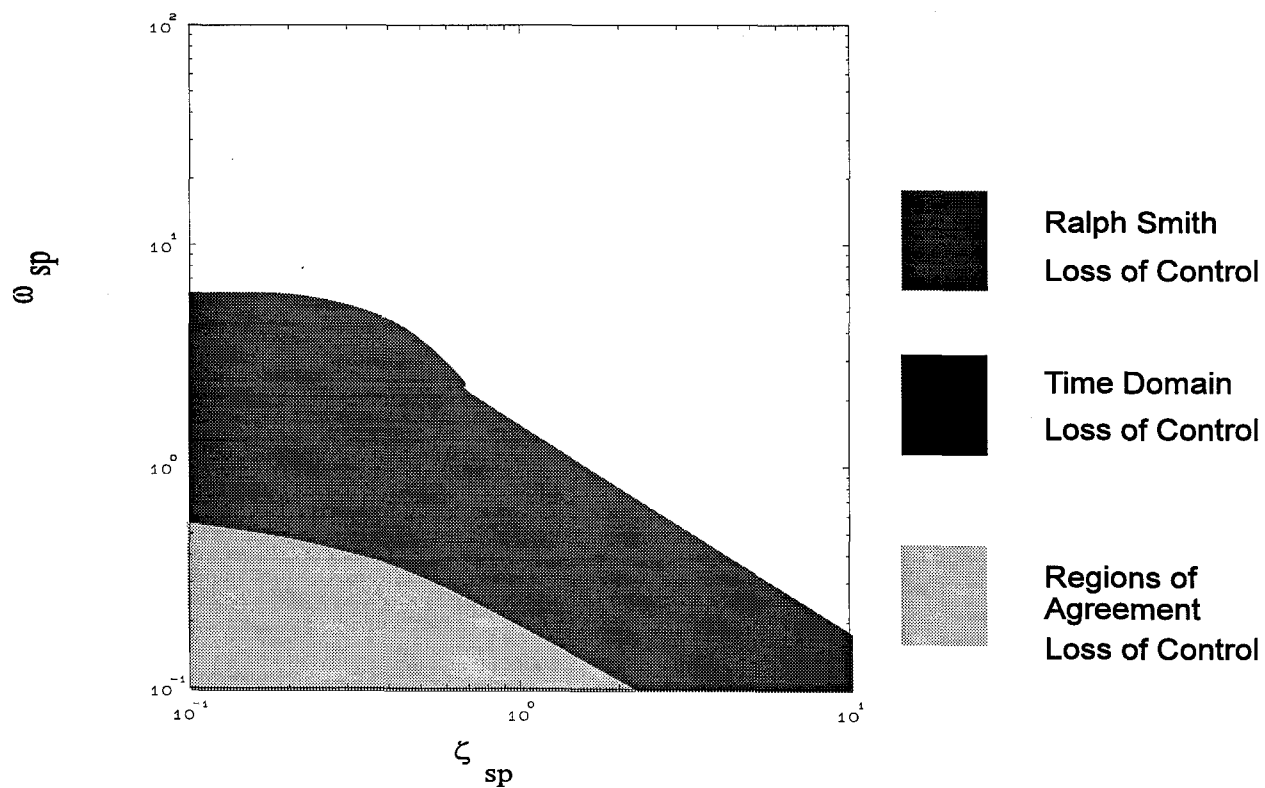


Figure C.90: Loss of Control Regions (Case 15)

C.16 Case 16

$$\frac{\theta(s)}{\delta(s)} = \frac{.237(2.12s + 1)e^{-.2s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

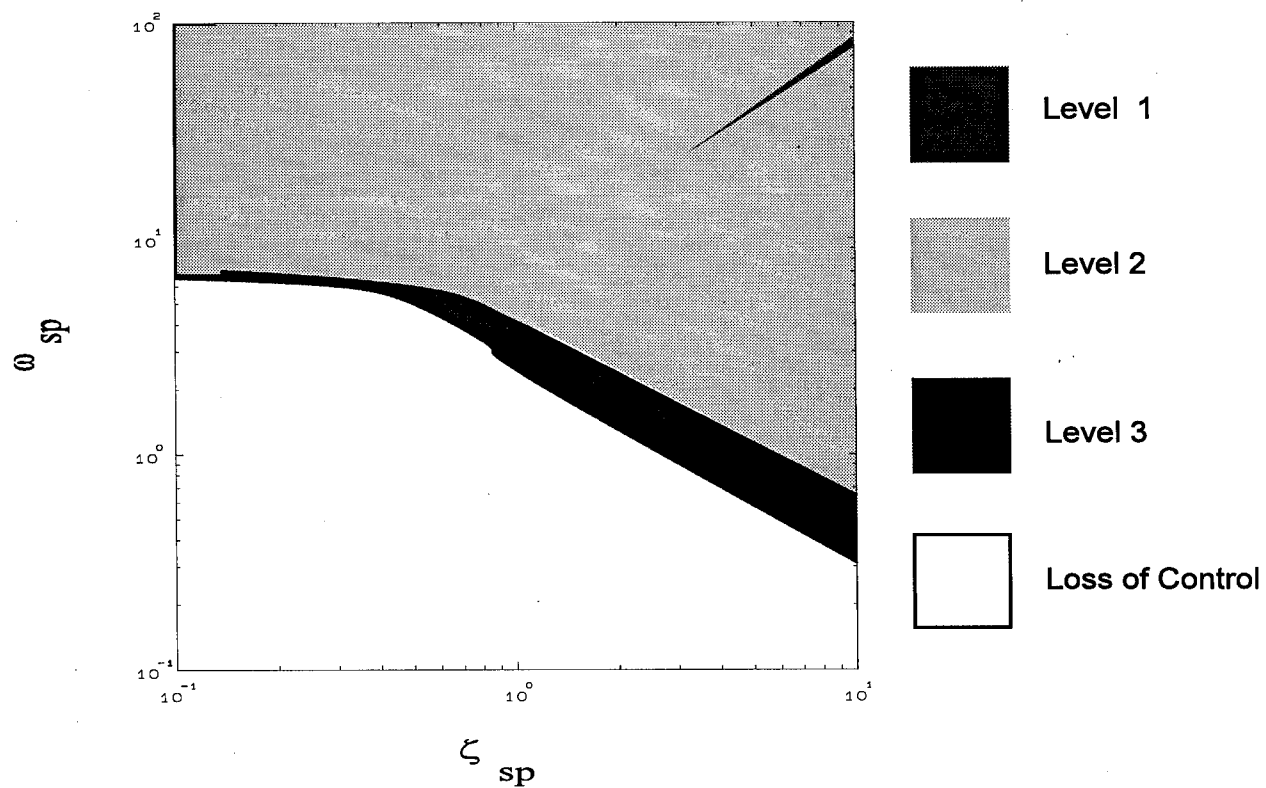


Figure C.91: Ralph Smith Criteria (Case 16)

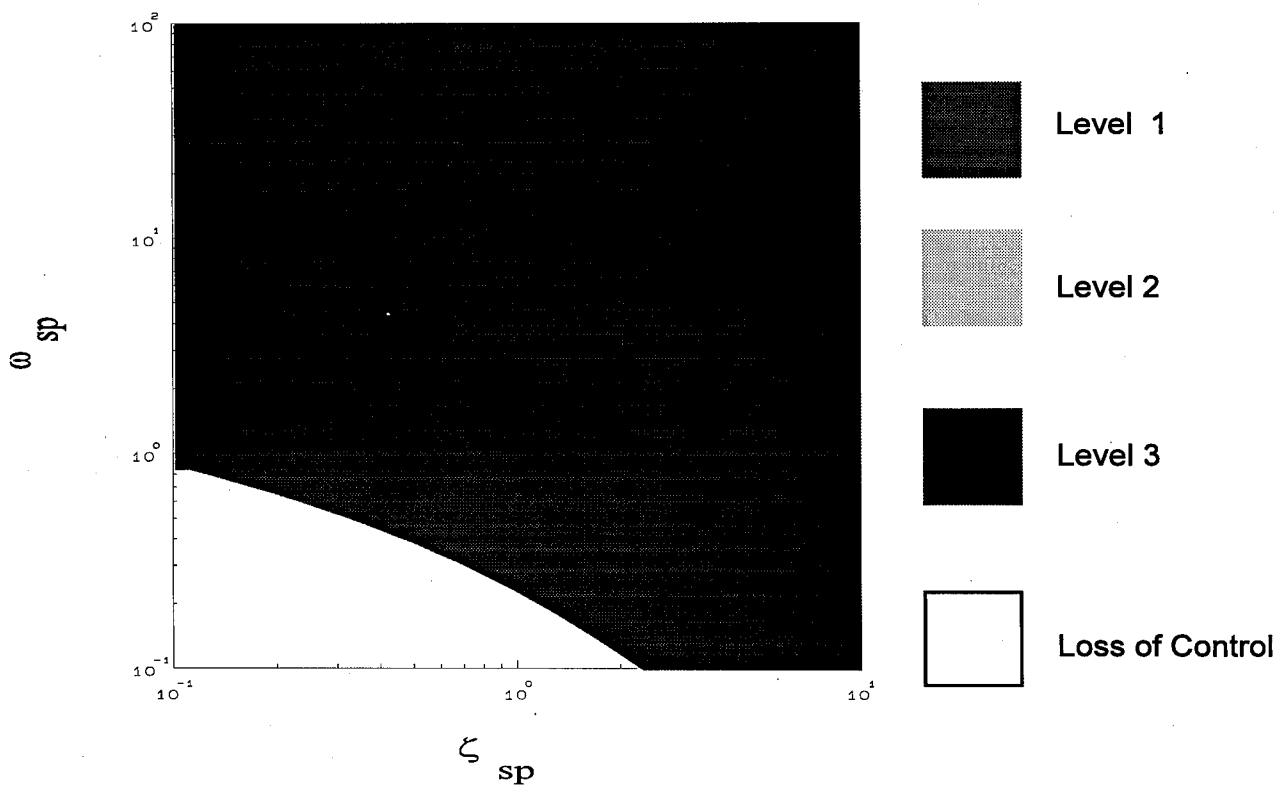


Figure C.92: Time Domain Criteria (Case 16)

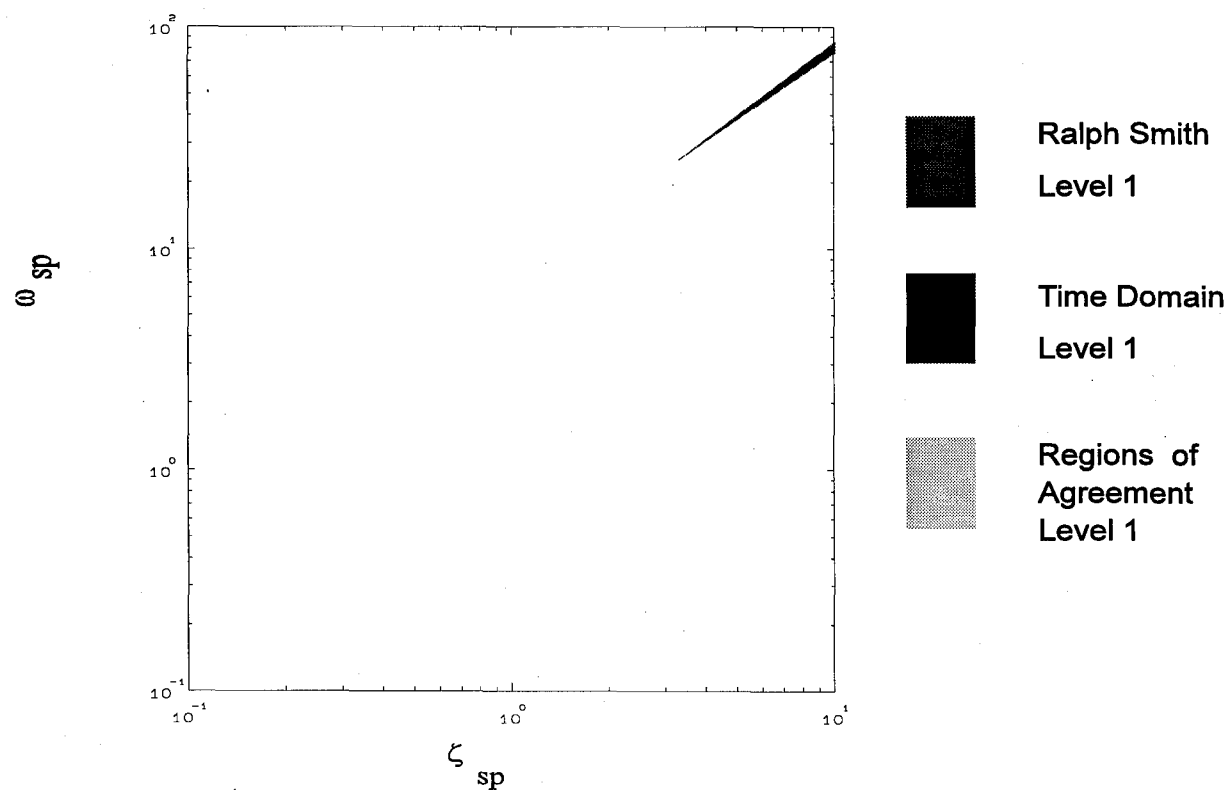


Figure C.93: Level 1 Regions (Case 16)

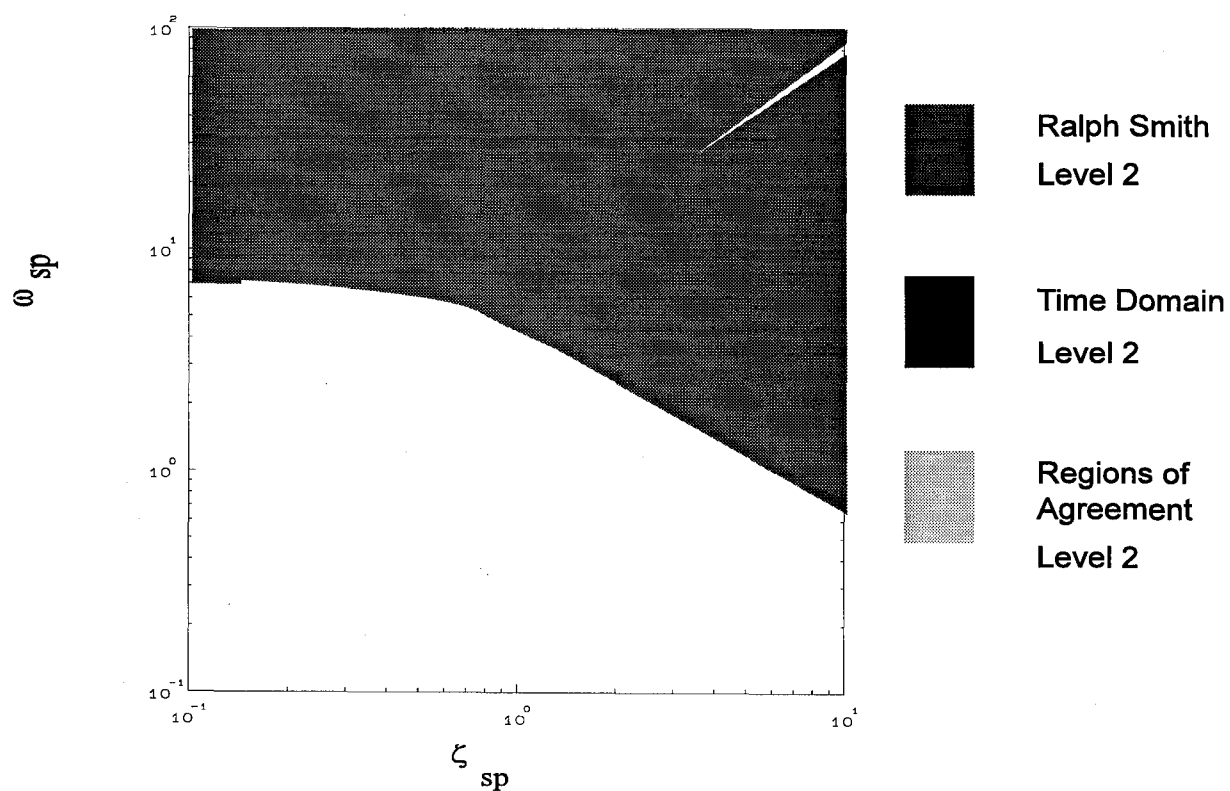


Figure C.94: Level 2 Regions (Case 16)

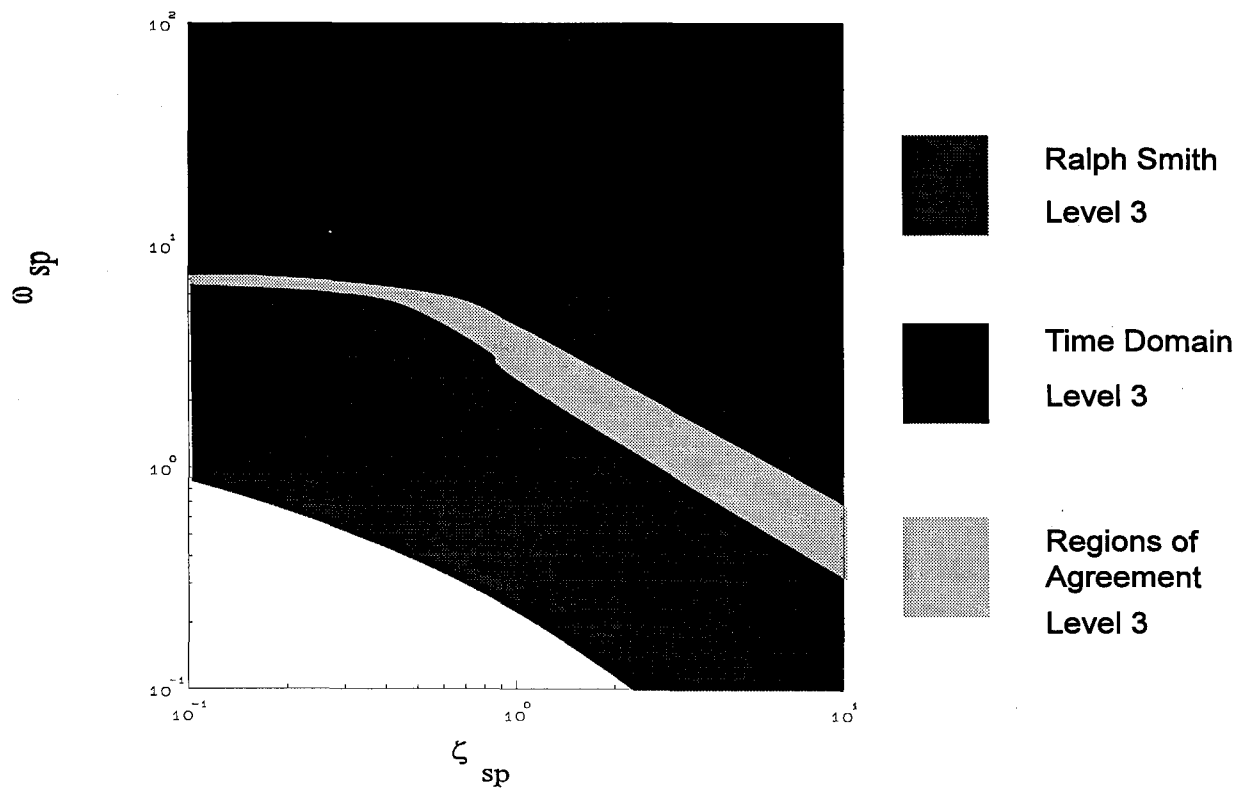


Figure C.95: Level 3 Regions (Case 16)

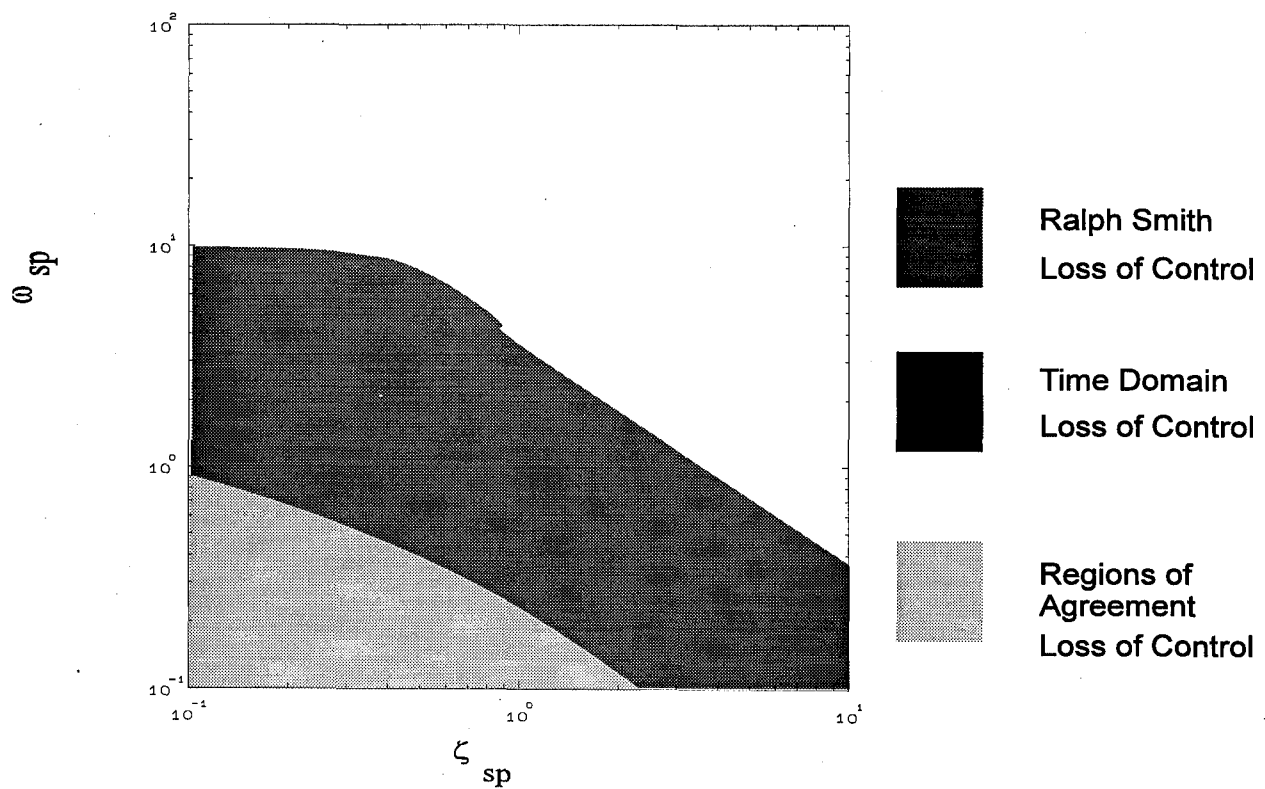


Figure C.96: Loss of Control Regions (Case 16)

C.17 Case 17

F-16 Transfer Function II

$$\frac{\theta(s)}{\delta(s)} = \frac{.1144(1.69s + 1)e^{0s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

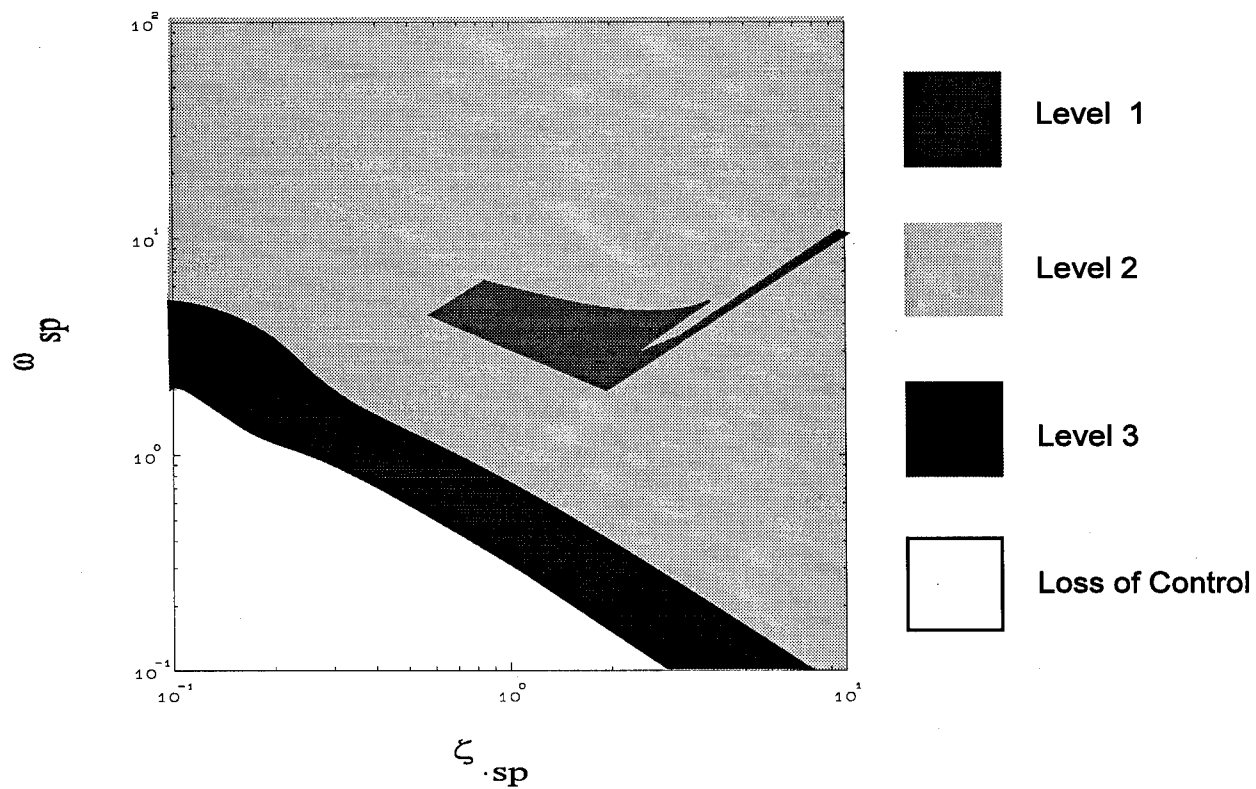


Figure C.97: Ralph Smith Criteria (Case 17)

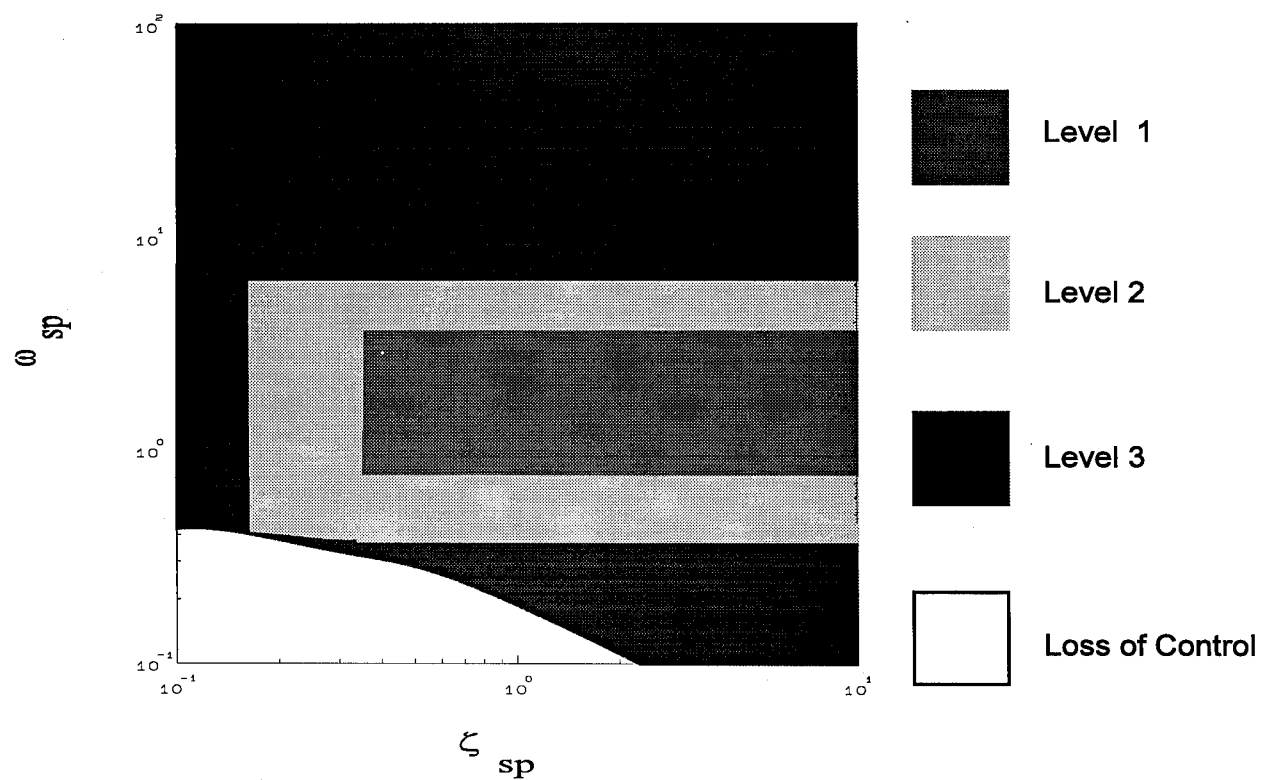


Figure C.98: Time Domain Criteria (Case 17)

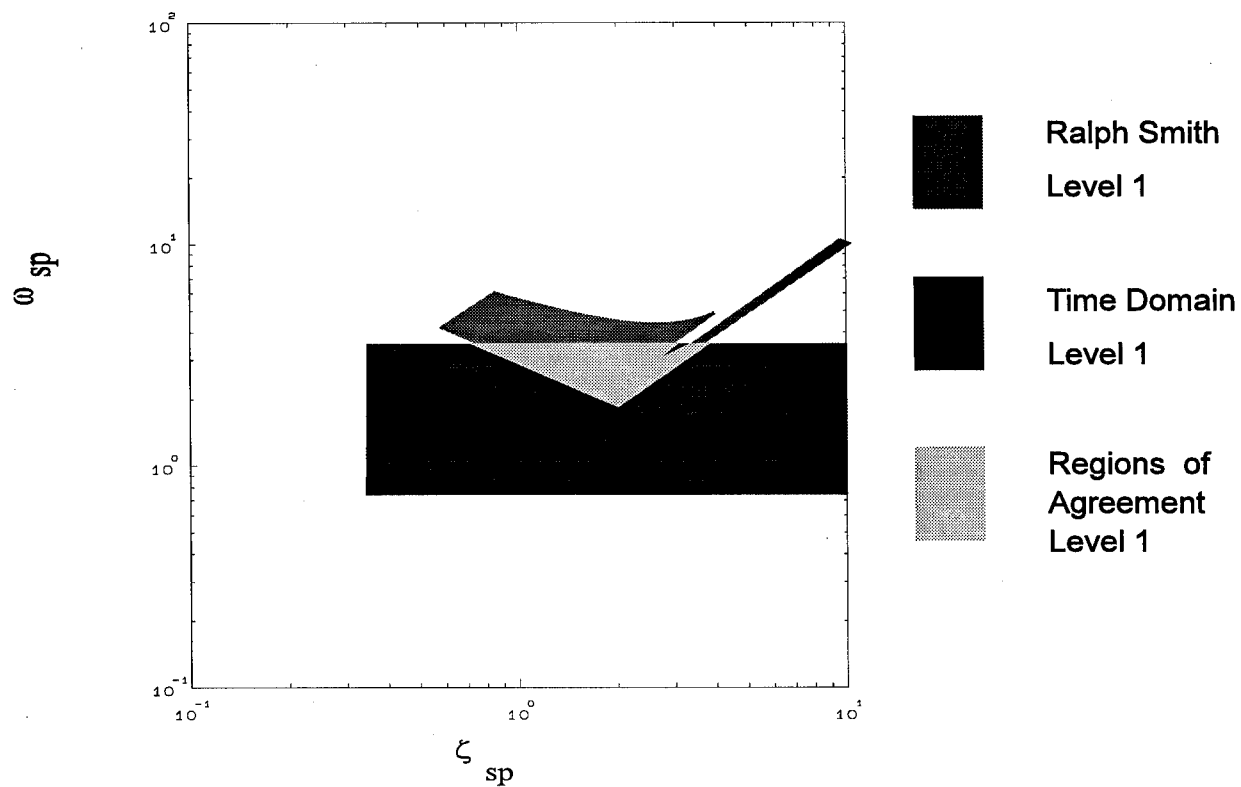


Figure C.99: Level 1 Regions (Case 17)

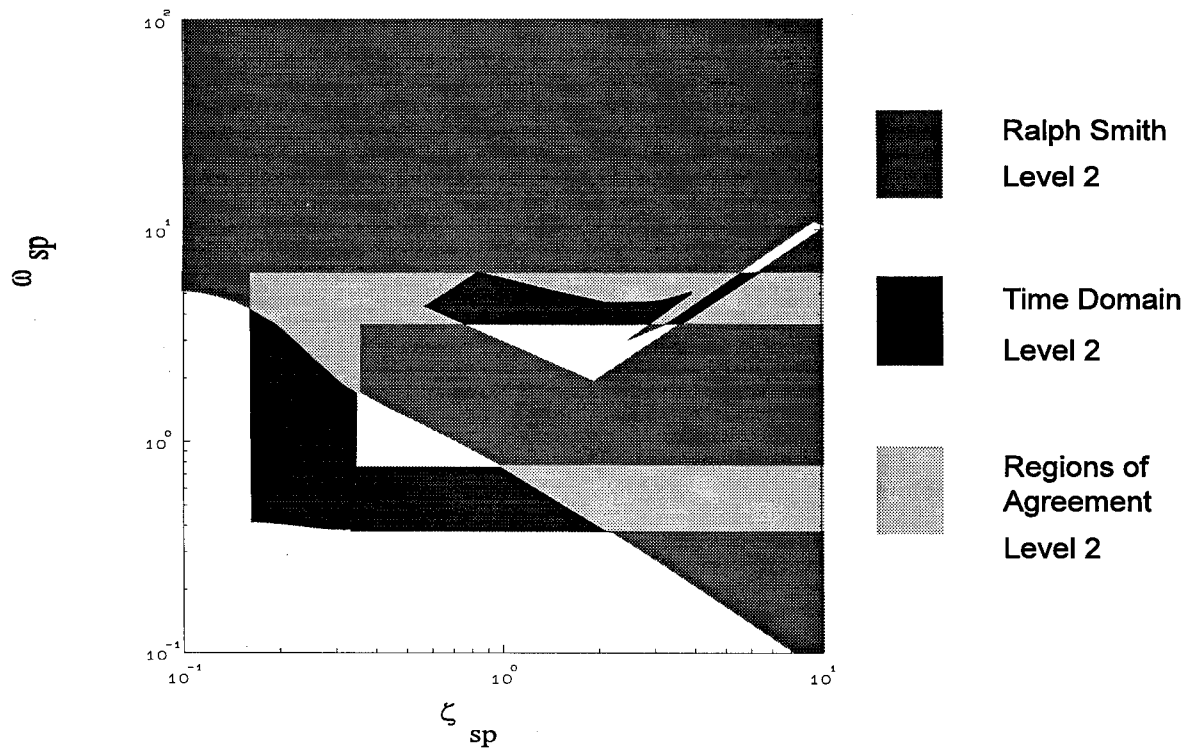


Figure C.100: Level 2 Regions (Case 17)

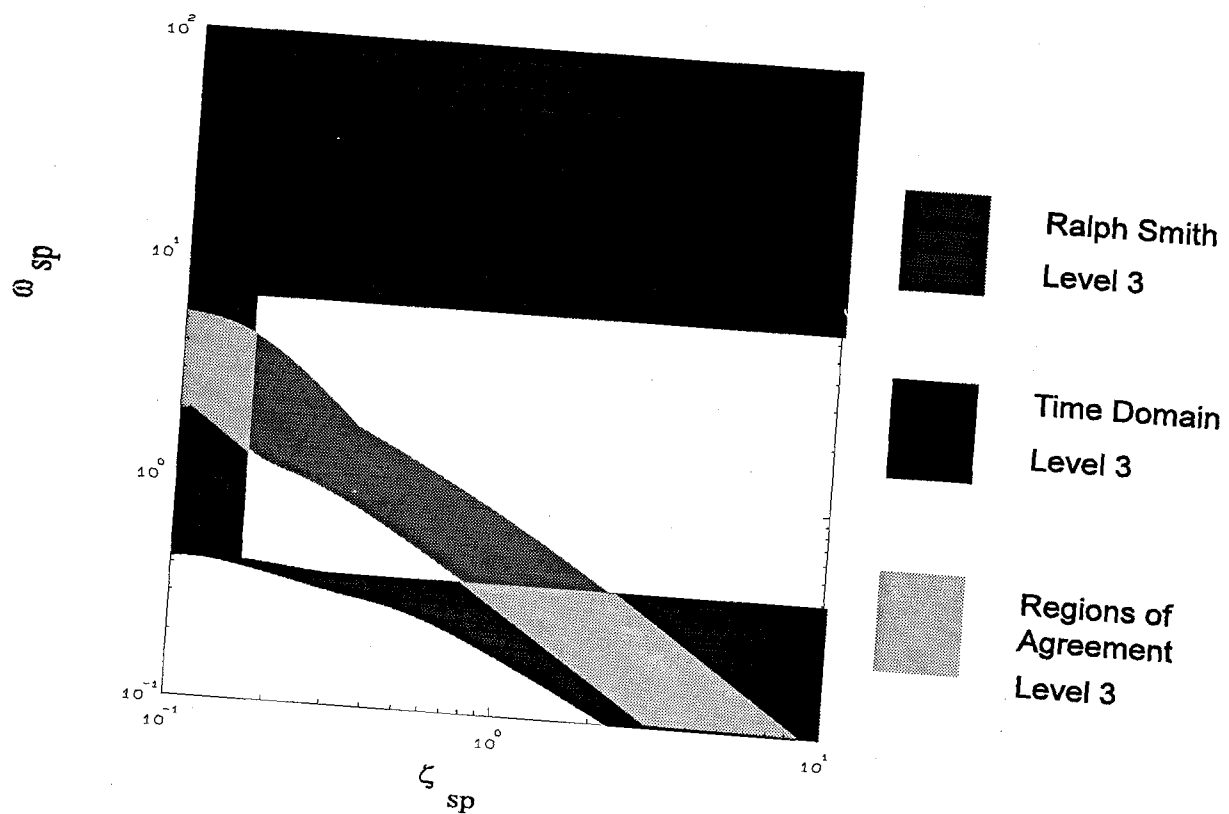


Figure C.101: Level 3 Regions (Case 17)

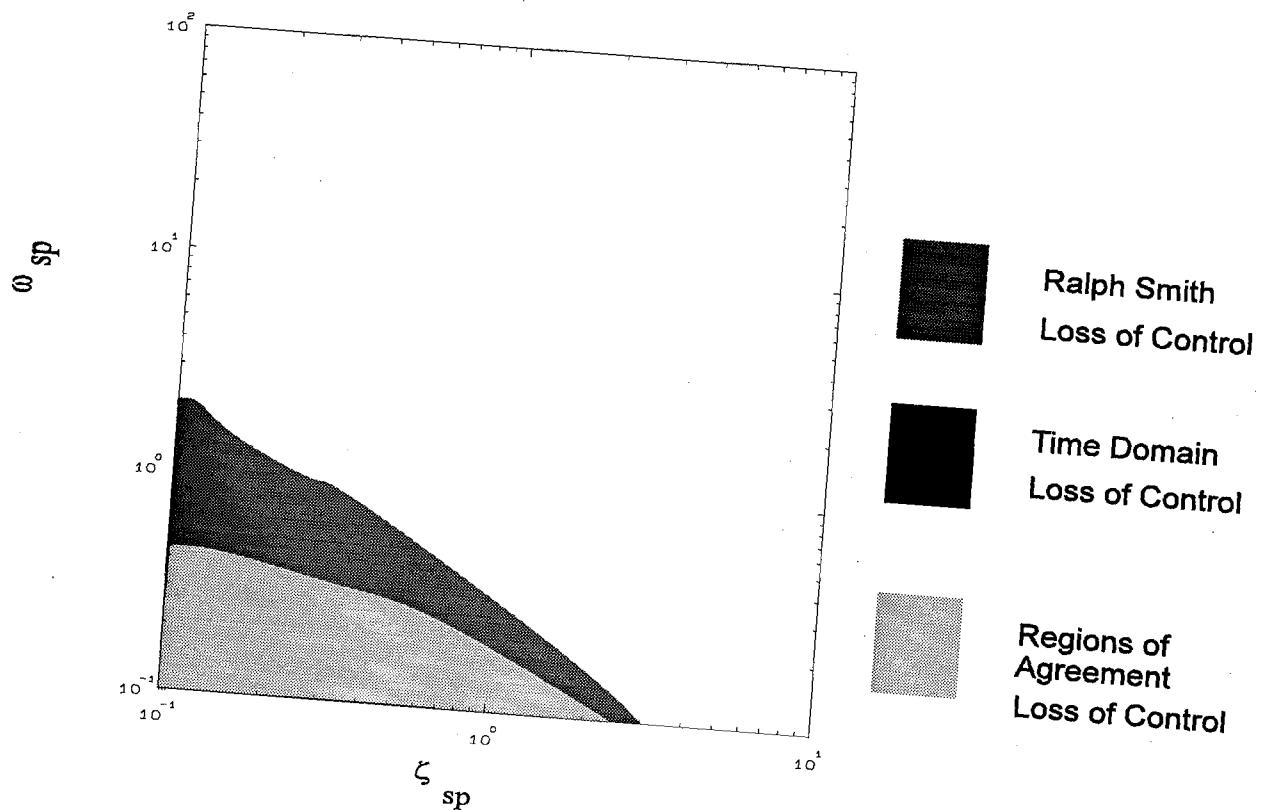
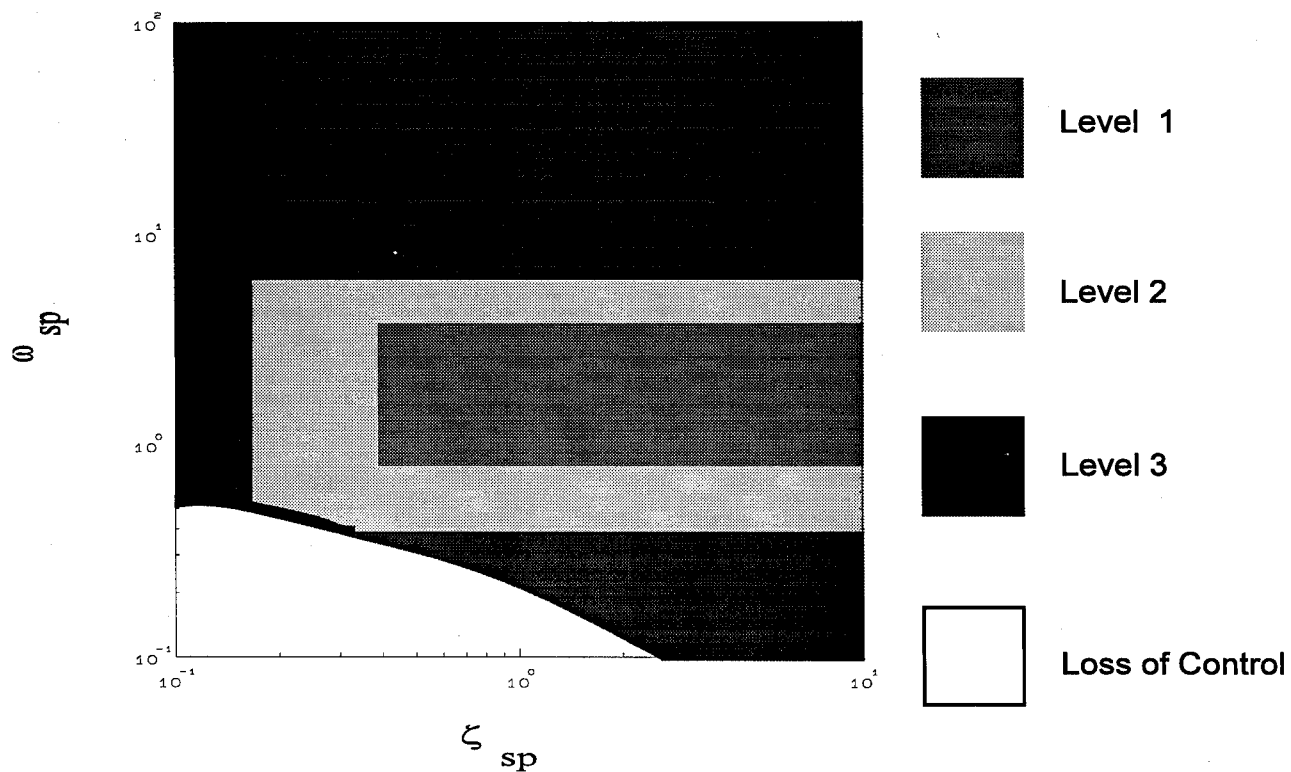
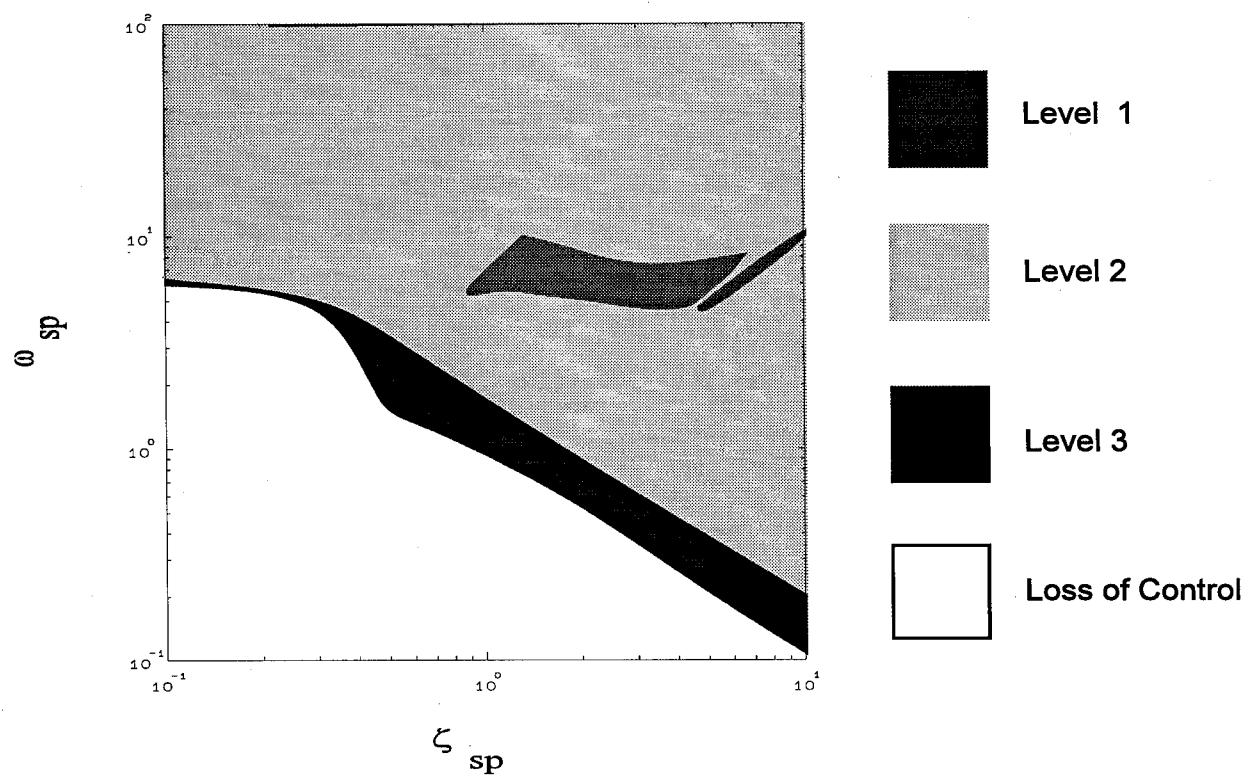
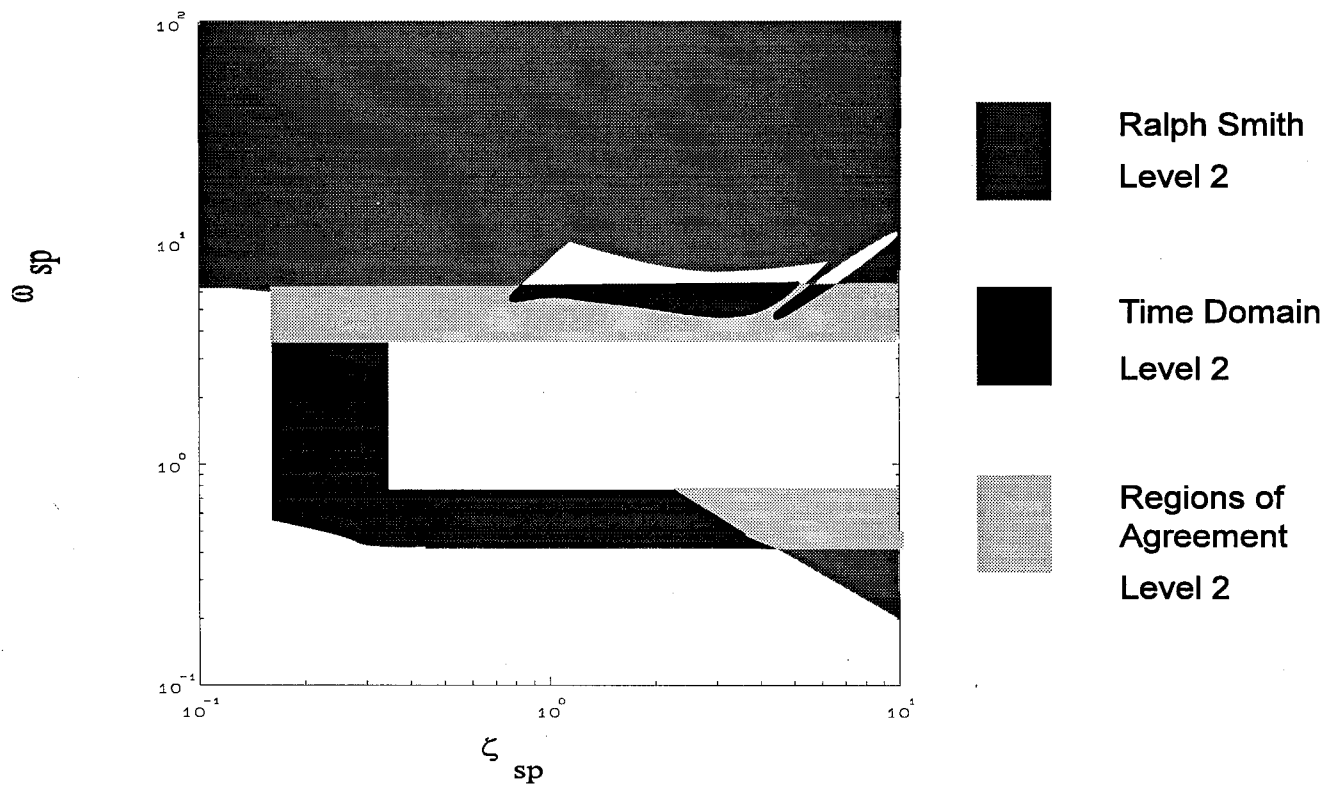
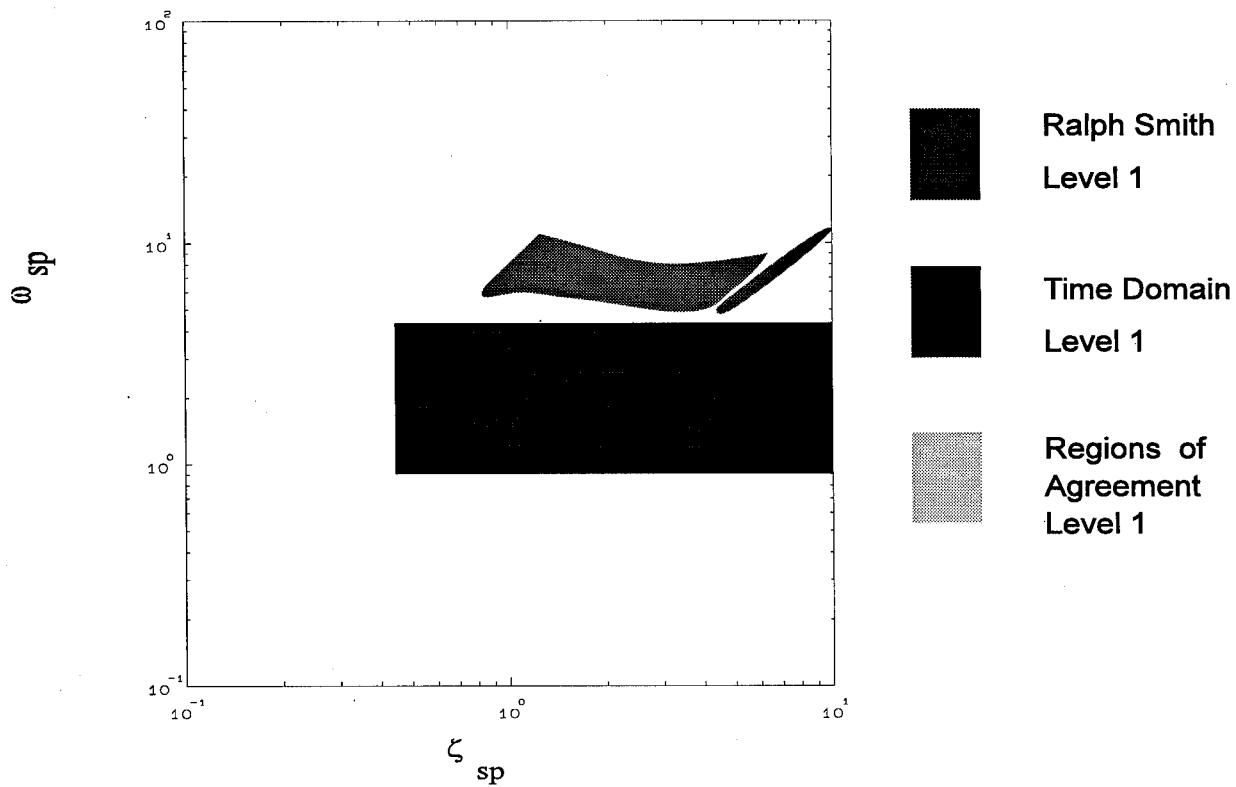


Figure C.102: Loss of Control Regions (Case 17)

C.18 Case 18

$$\frac{\theta(s)}{\delta(s)} = \frac{.1144(1.69s + 1)e^{-.1s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$





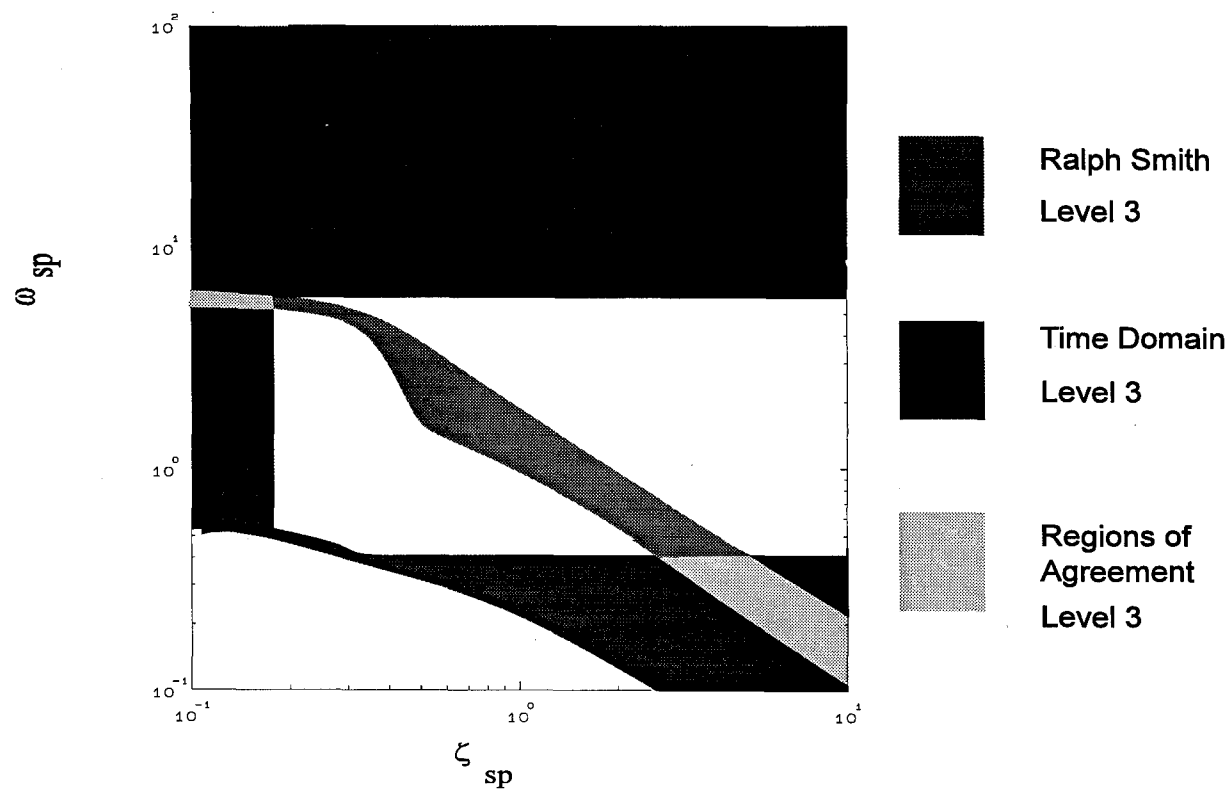


Figure C.107: Level 3 Regions (Case 18)

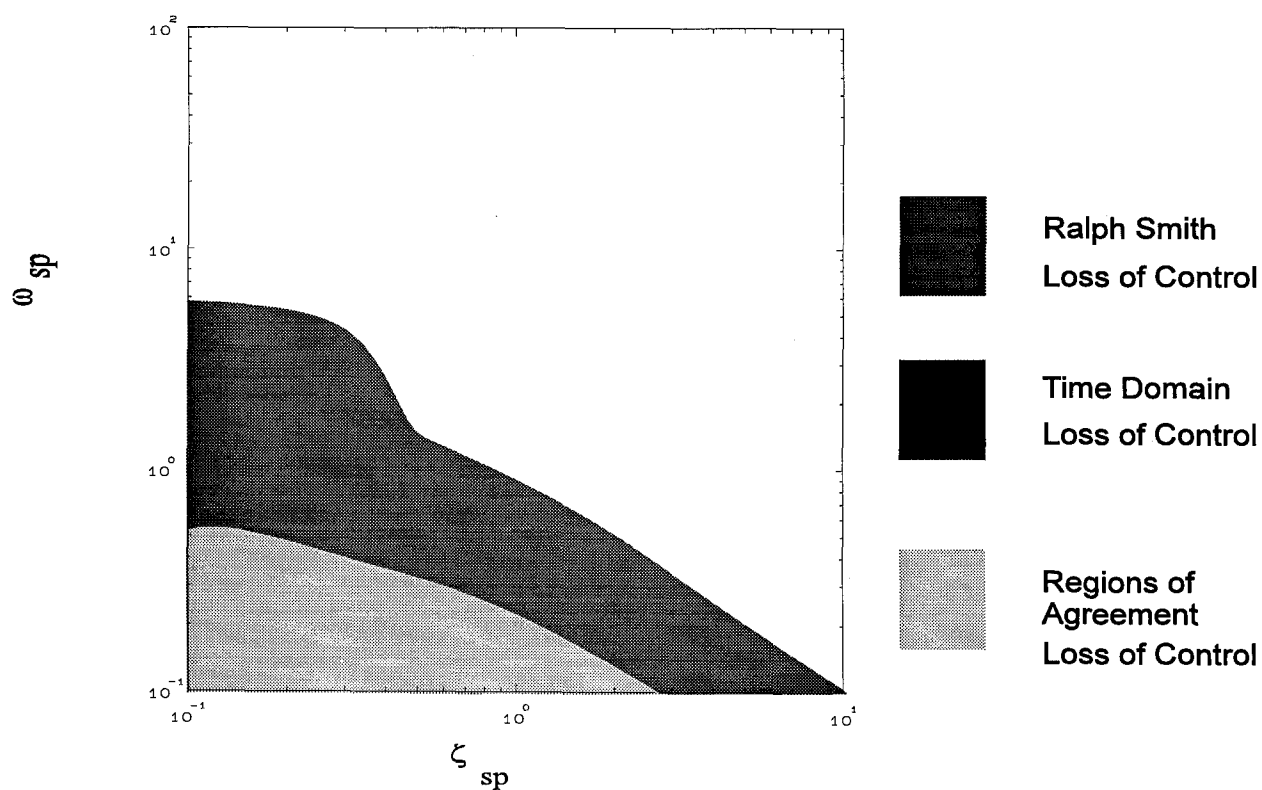


Figure C.108: Loss of Control Regions (Case 18)

C.19 Case 19

$$\frac{\theta(s)}{\delta(s)} = \frac{.1144(1.69s + 1)e^{-.15s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

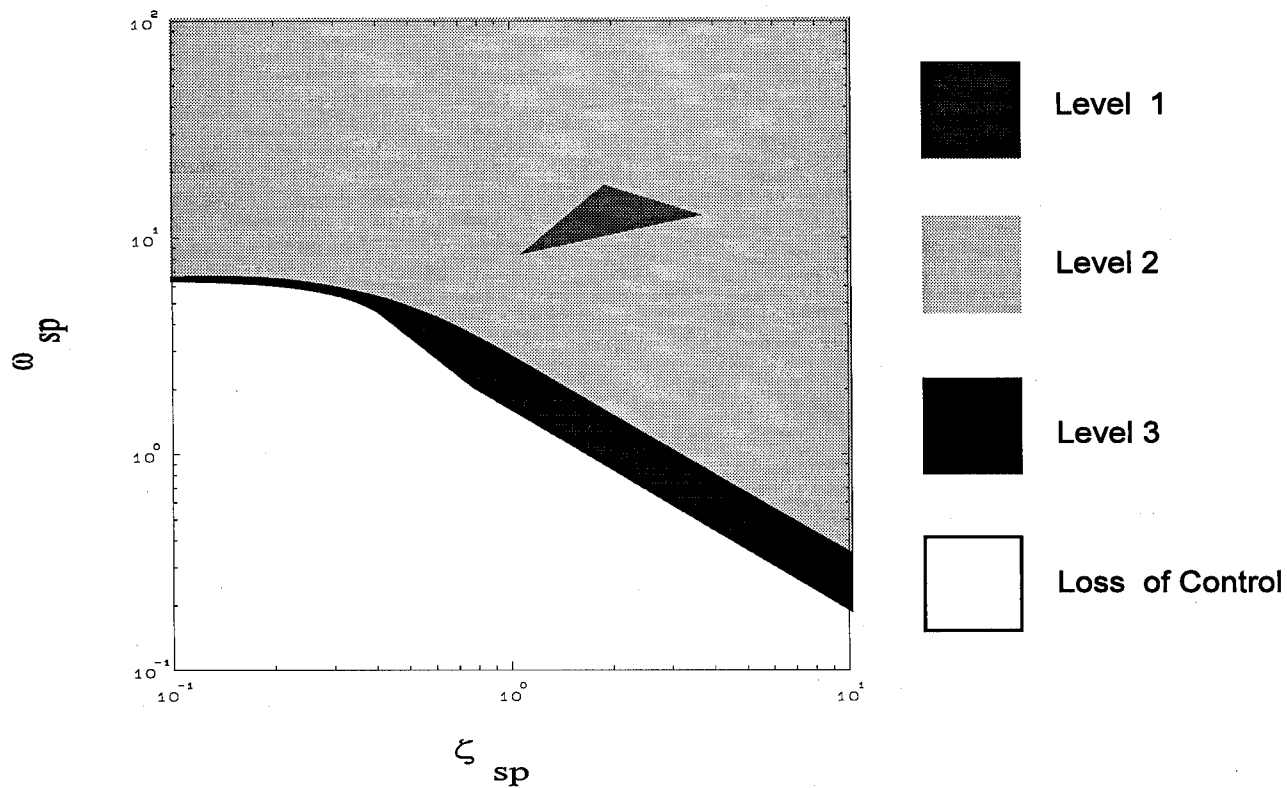


Figure C.109: Ralph Smith Criteria (Case 19)

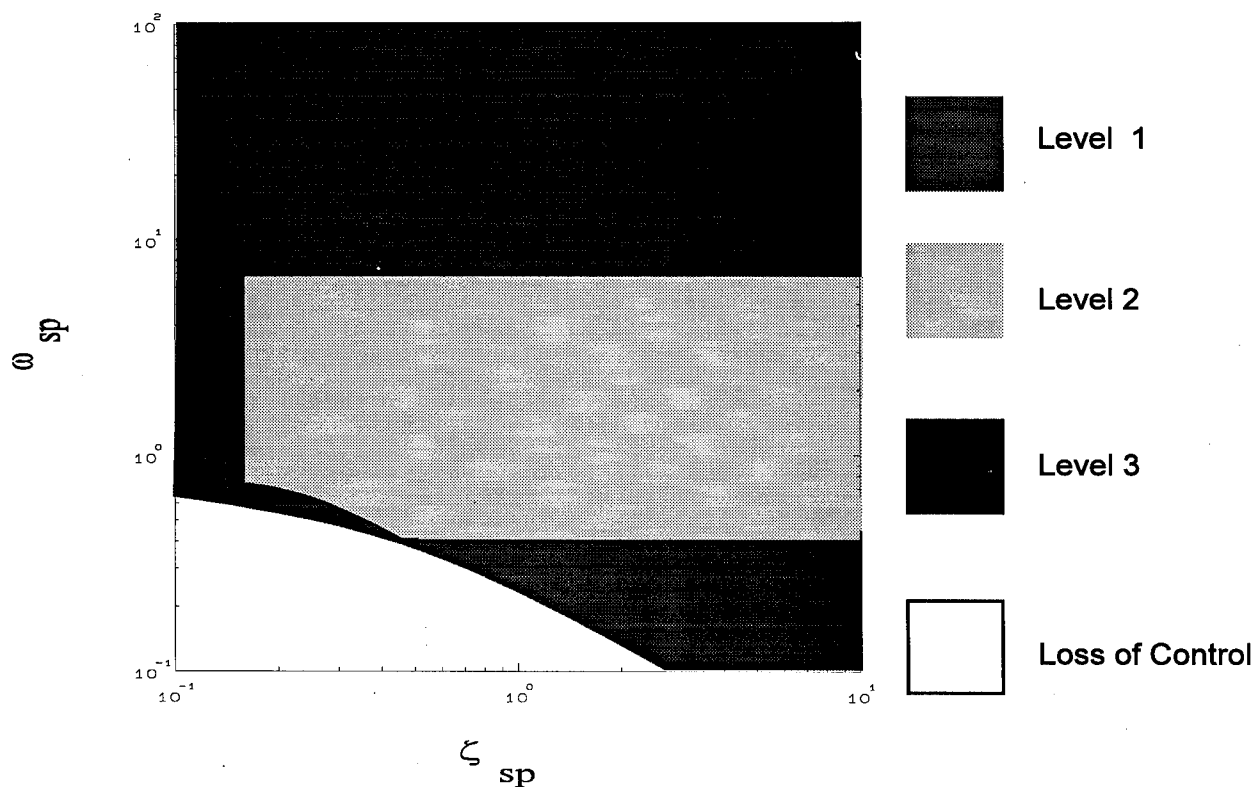


Figure C.110: Time Domain Criteria (Case 19)

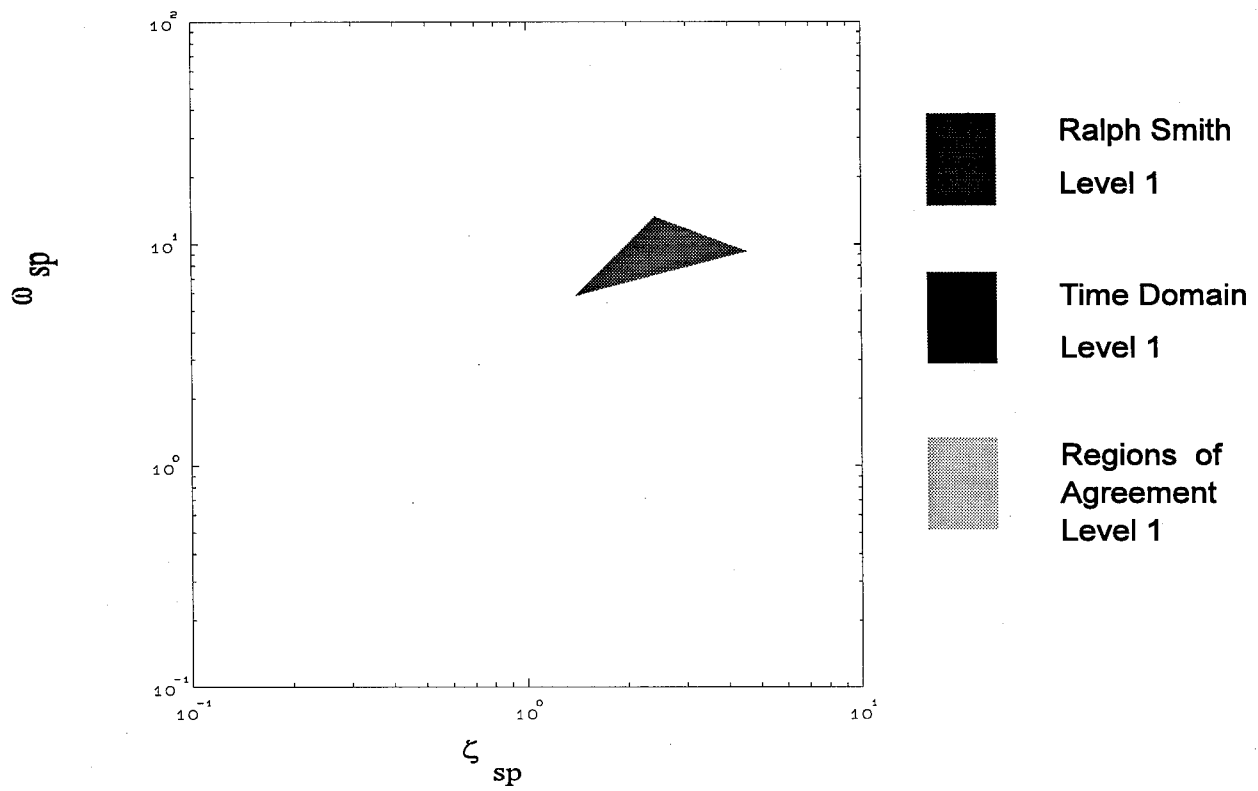


Figure C.111: Level 1 Regions (Case 19)

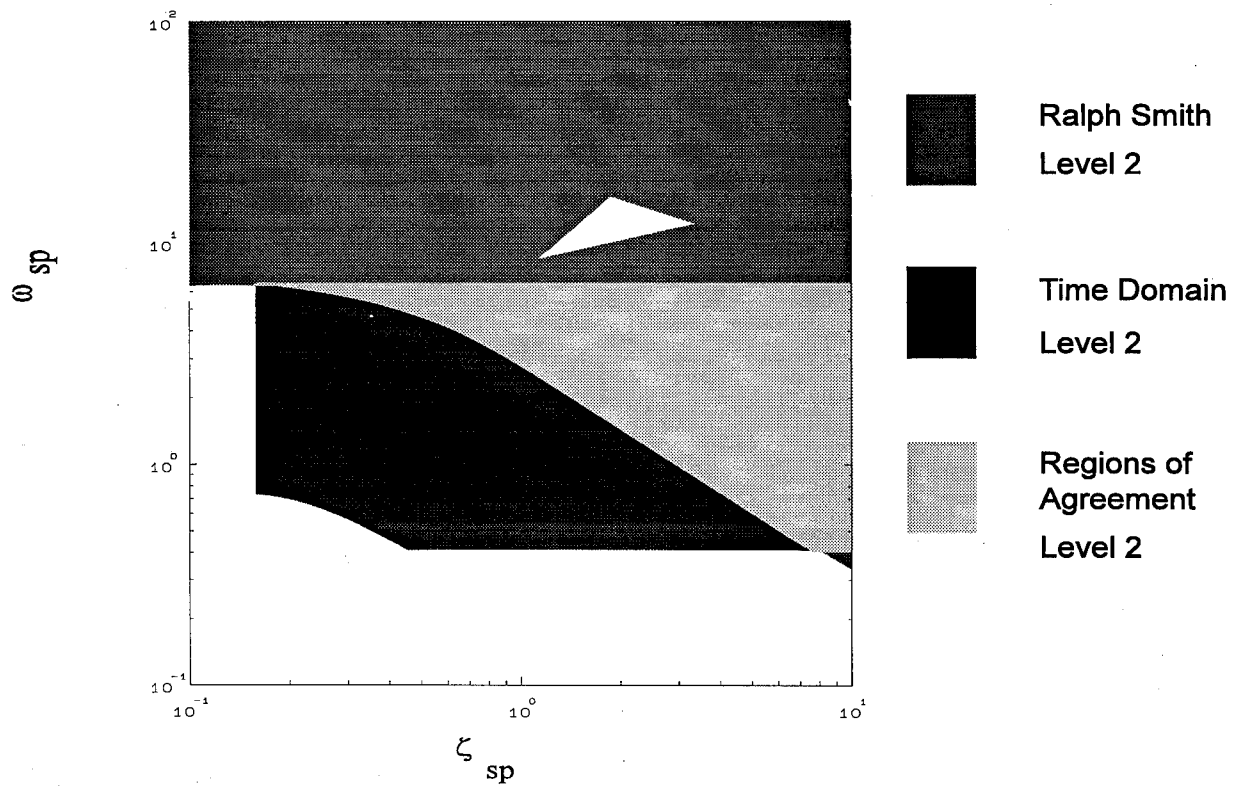


Figure C.112: Level 2 Regions (Case 19)

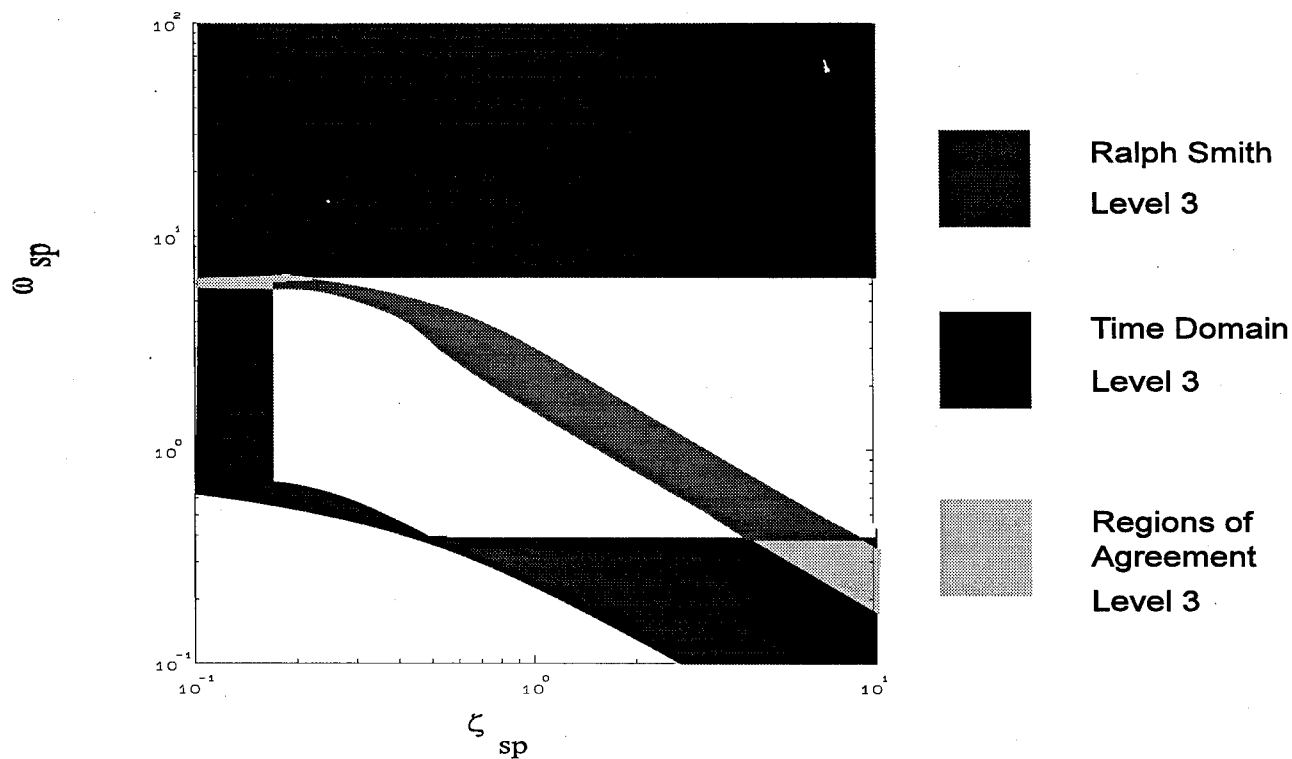


Figure C.113: Level 3 Regions (Case 19)

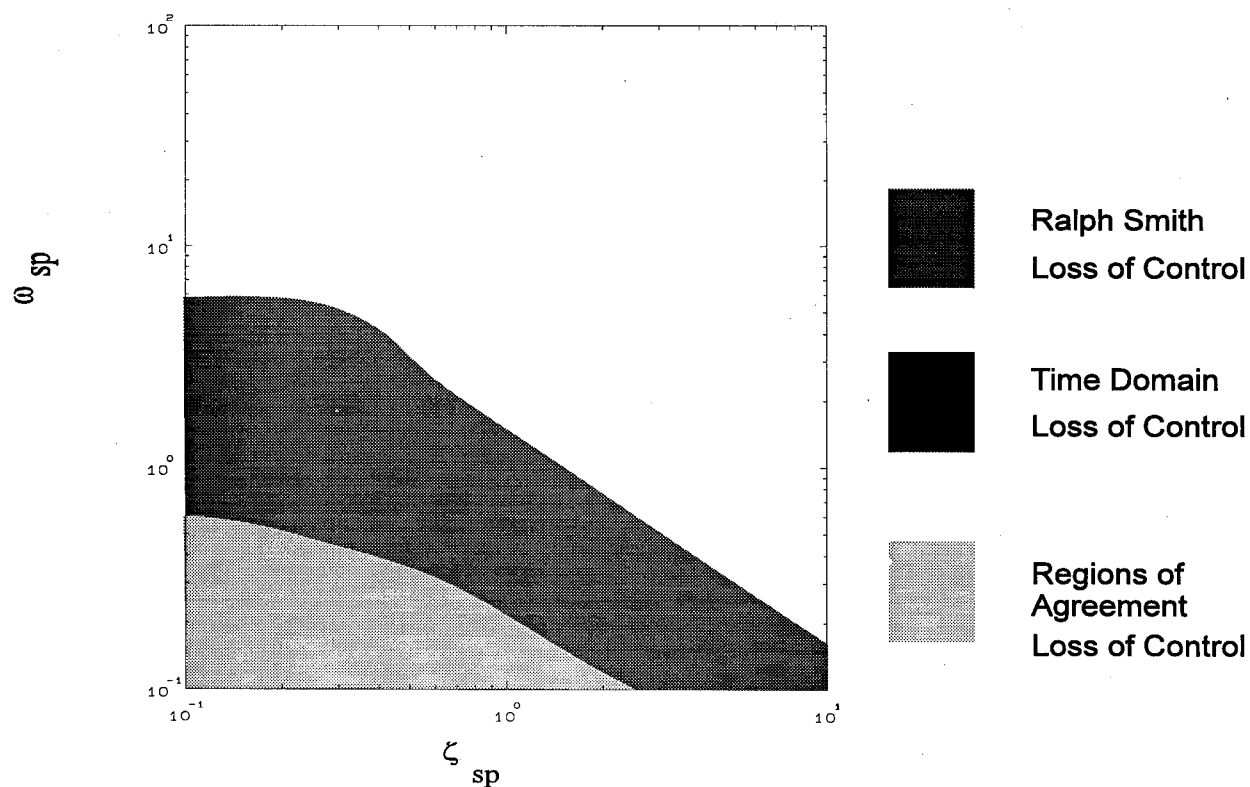


Figure C.114: Loss of Control Regions (Case 19)

C.20 Case 20

$$\frac{\theta(s)}{\delta(s)} = \frac{.1144(1.69s + 1)e^{-.2s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

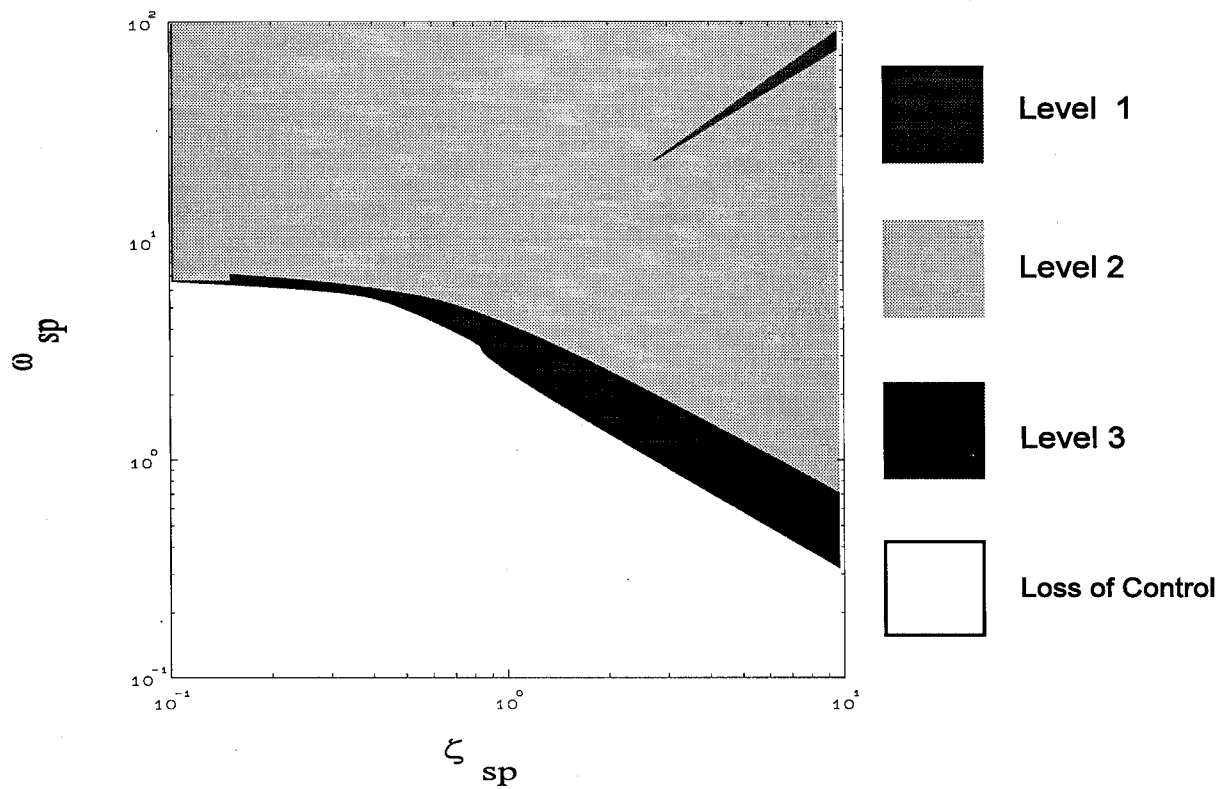


Figure C.115: Ralph Smith Criteria (Case 20)

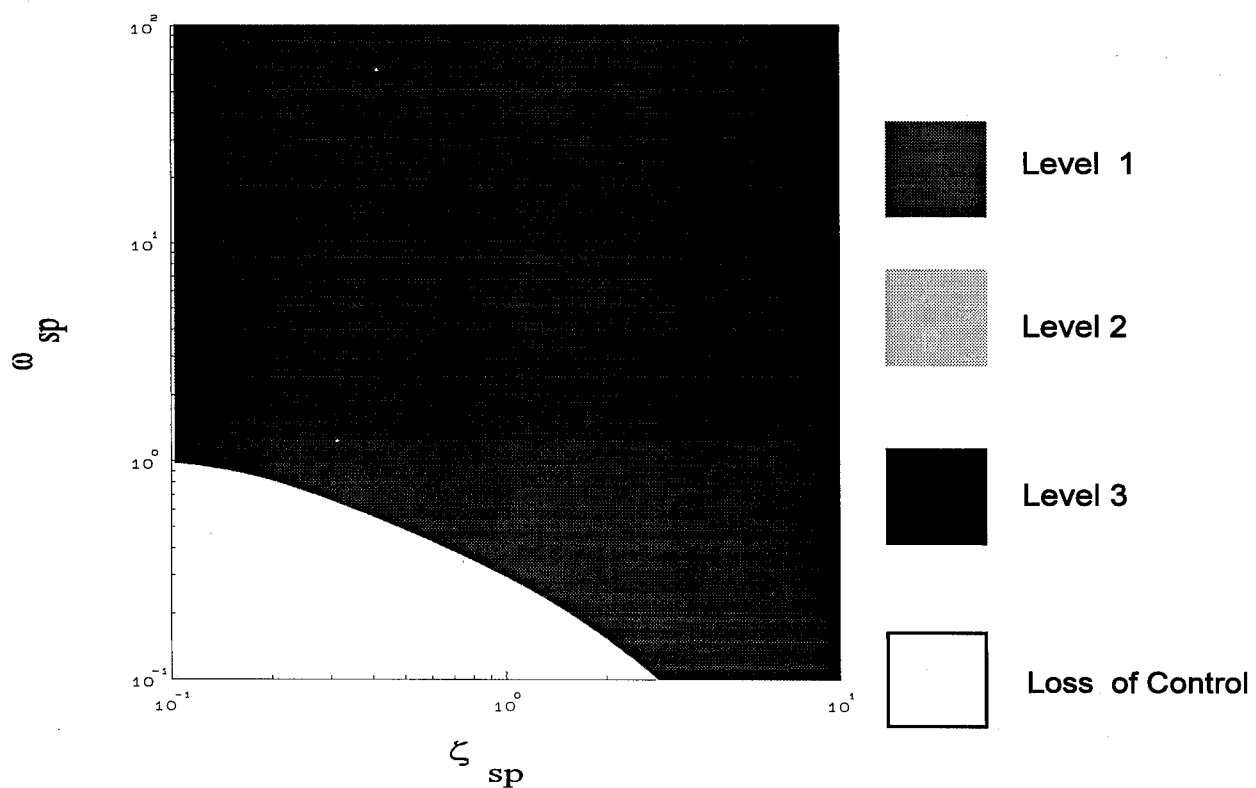


Figure C.116: Time Domain Criteria (Case 20)

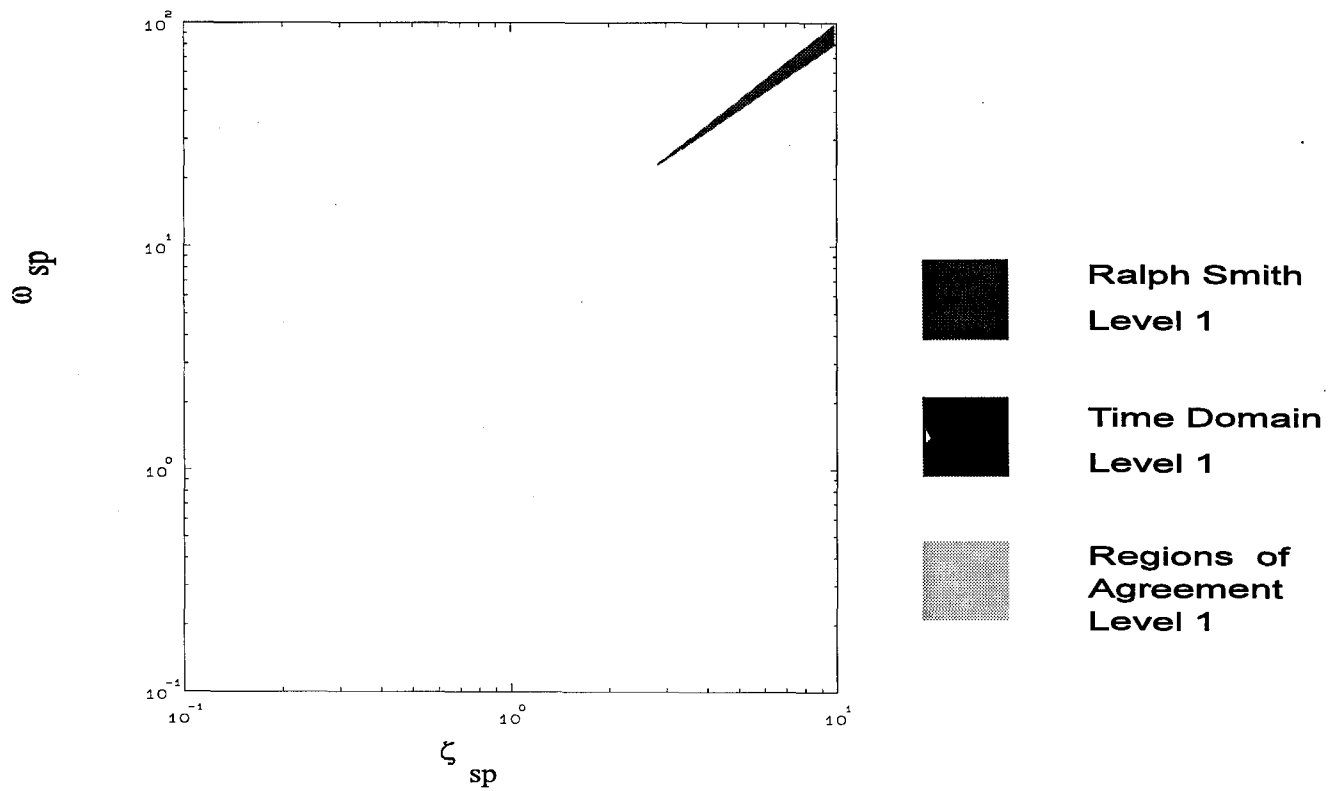


Figure C.117: Level 1 Regions (Case 20)

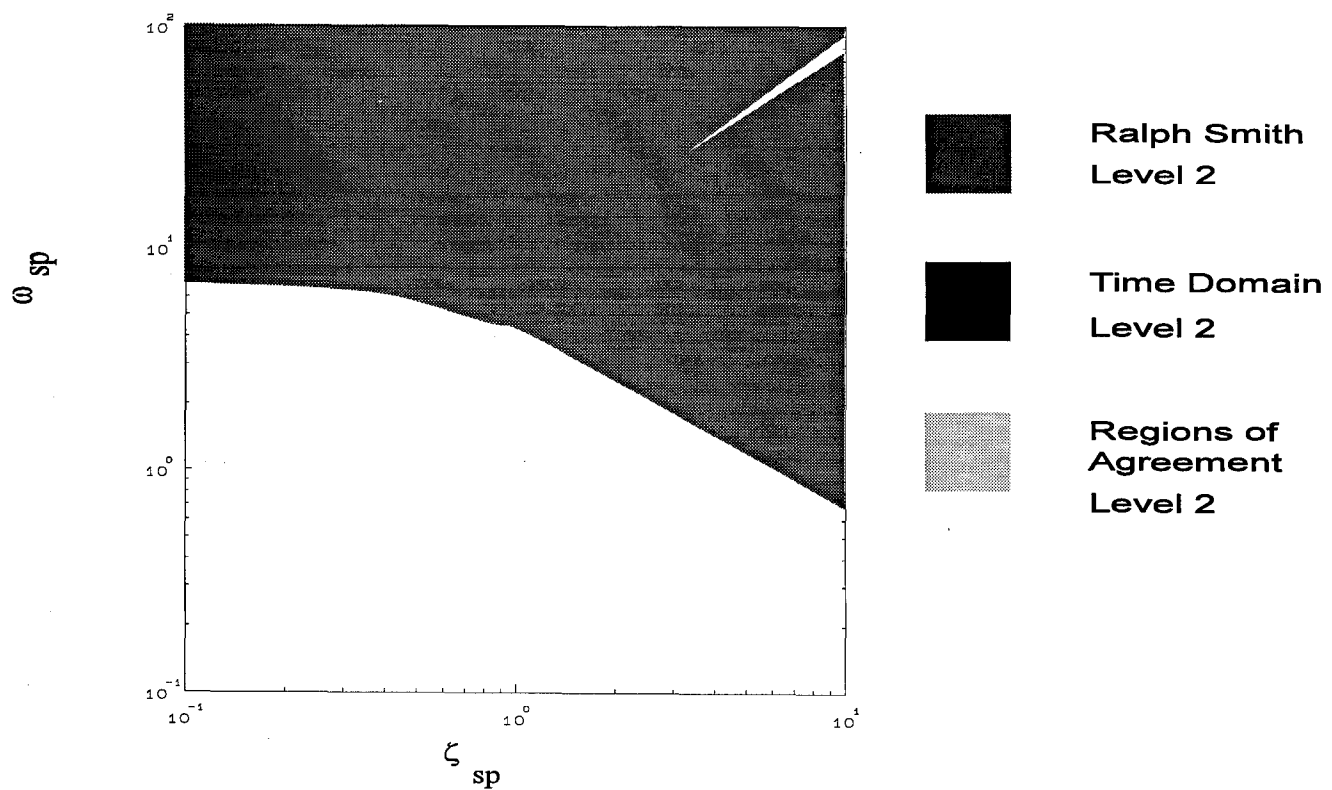


Figure C.118: Level 2 Regions (Case 20)

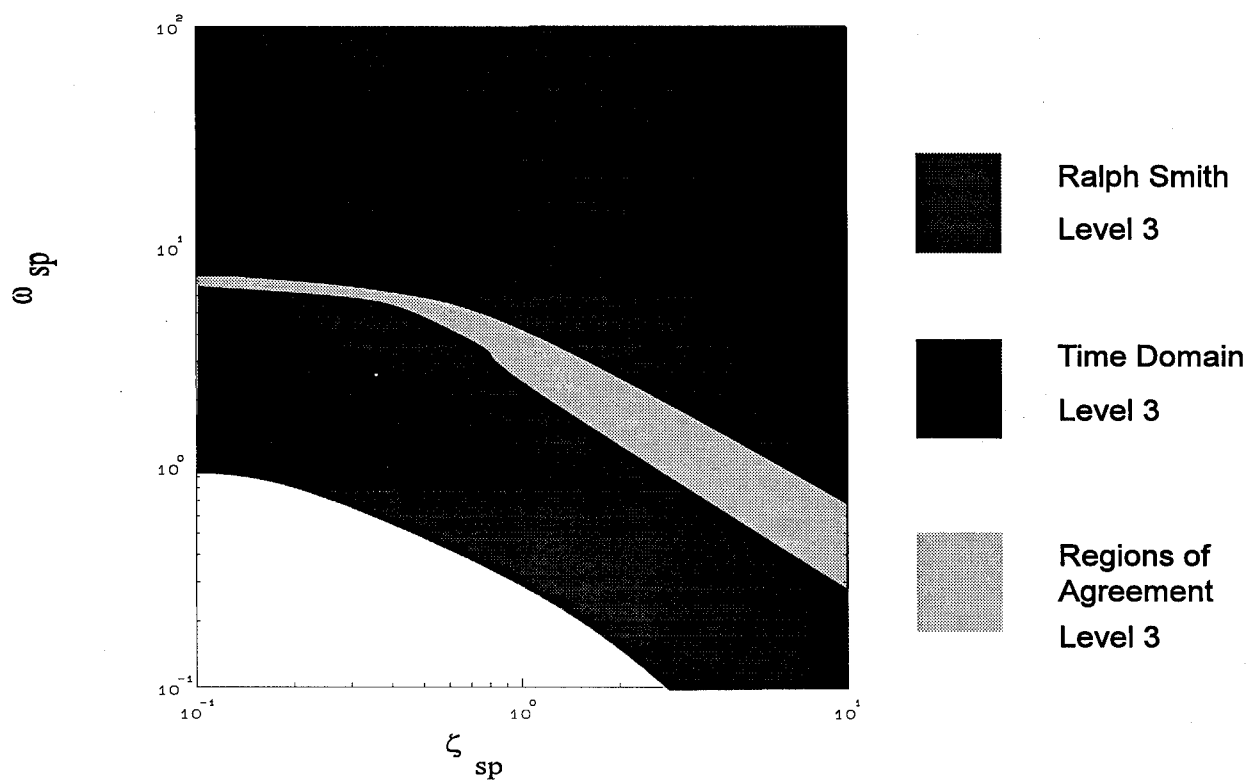


Figure C.119: Level 3 Regions (Case 20)

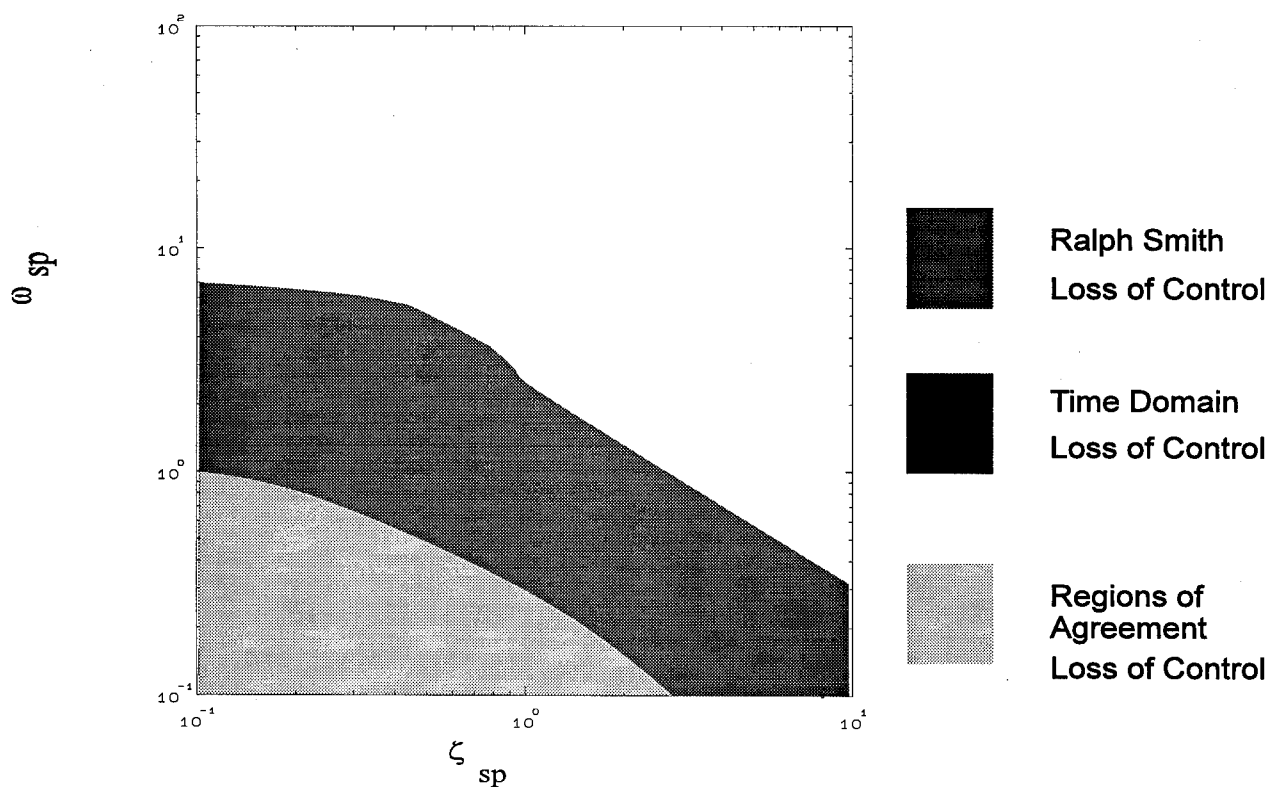


Figure C.120: Loss of Control Regions (Case 20)

C.21 Case 21

F-16 Transfer Function III

$$\frac{\theta(s)}{\delta(s)} = \frac{.1431(1.77s + 1)e^{0s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

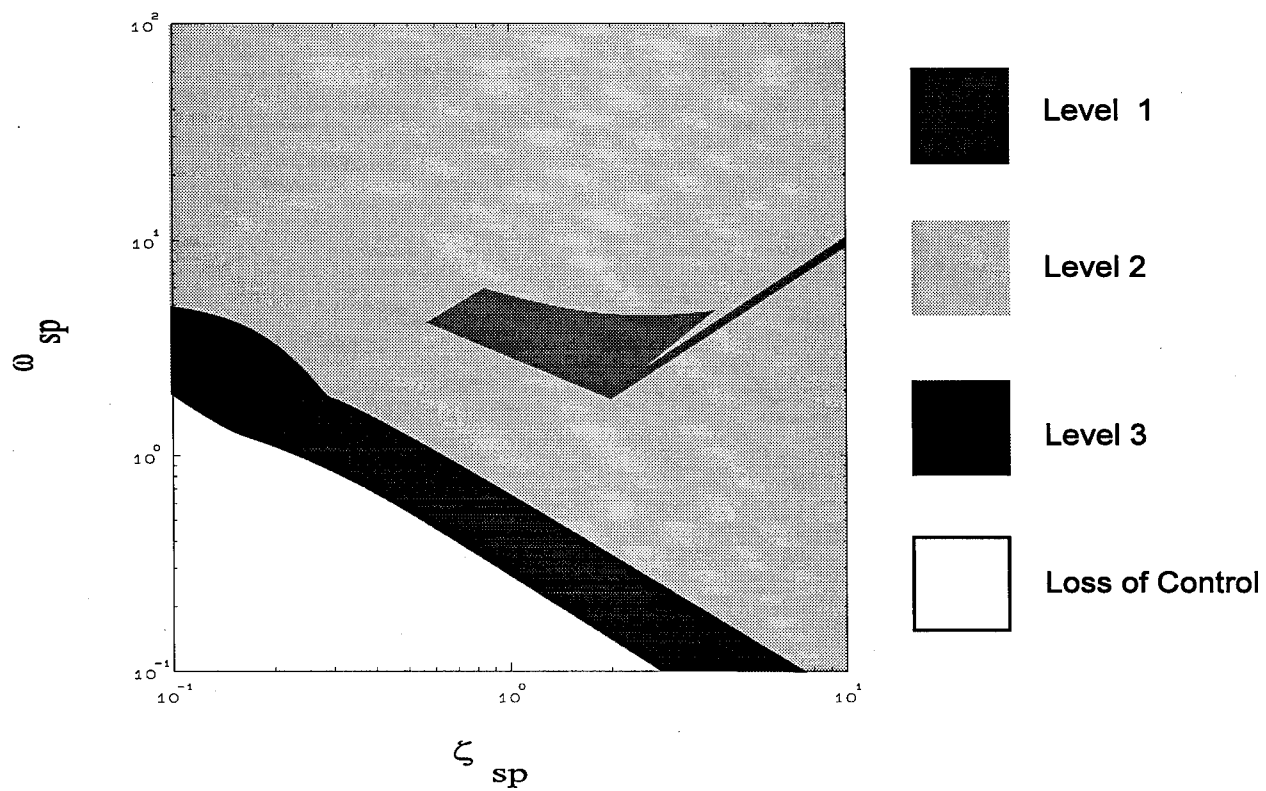


Figure C.121: Ralph Smith Criteria (Case 21)

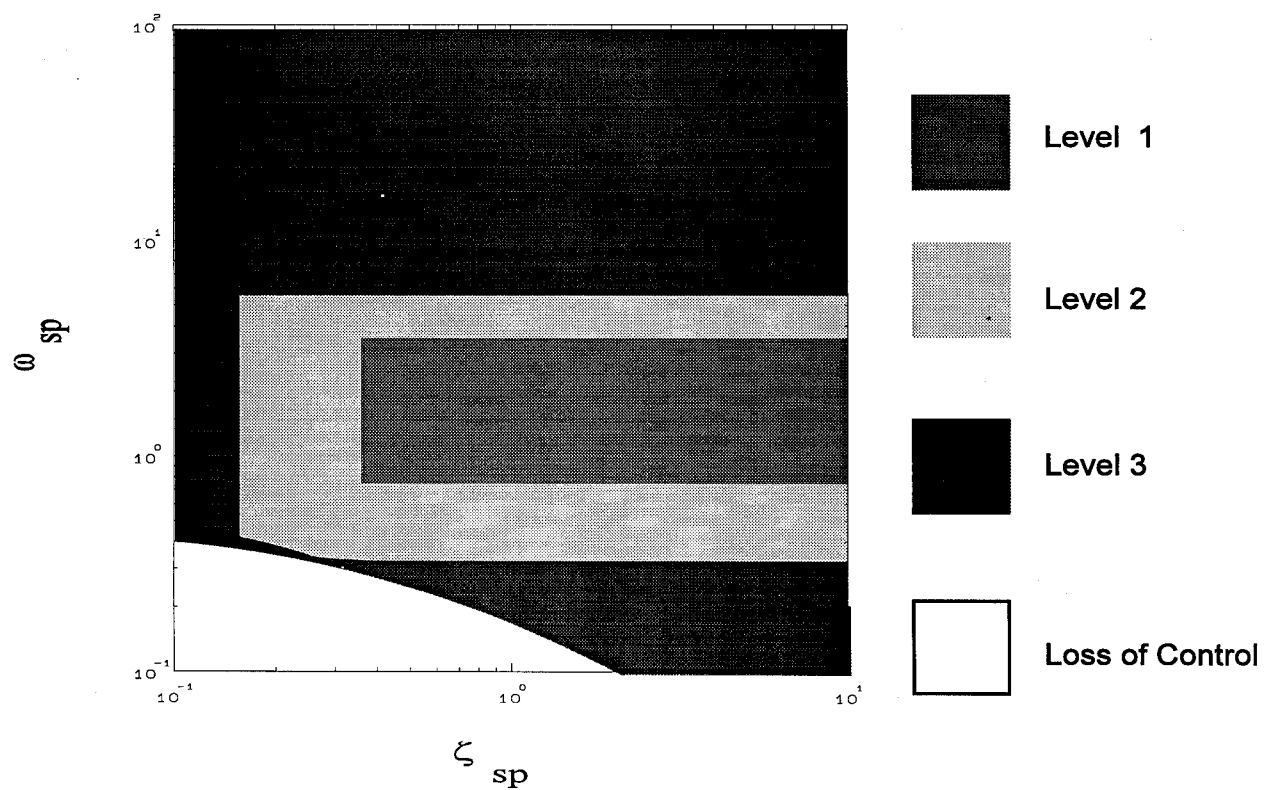


Figure C.122: Time Domain Criteria (Case 21)

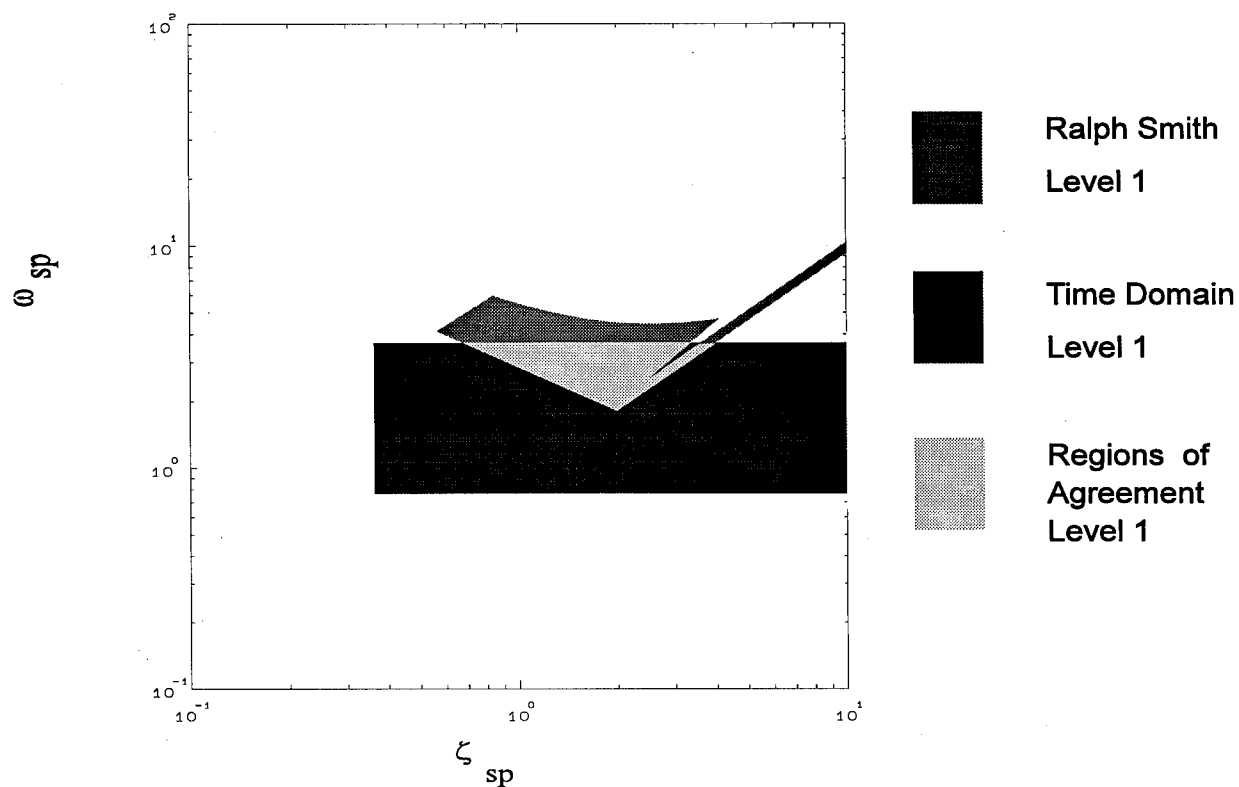


Figure C.123: Level 1 Regions (Case 21)

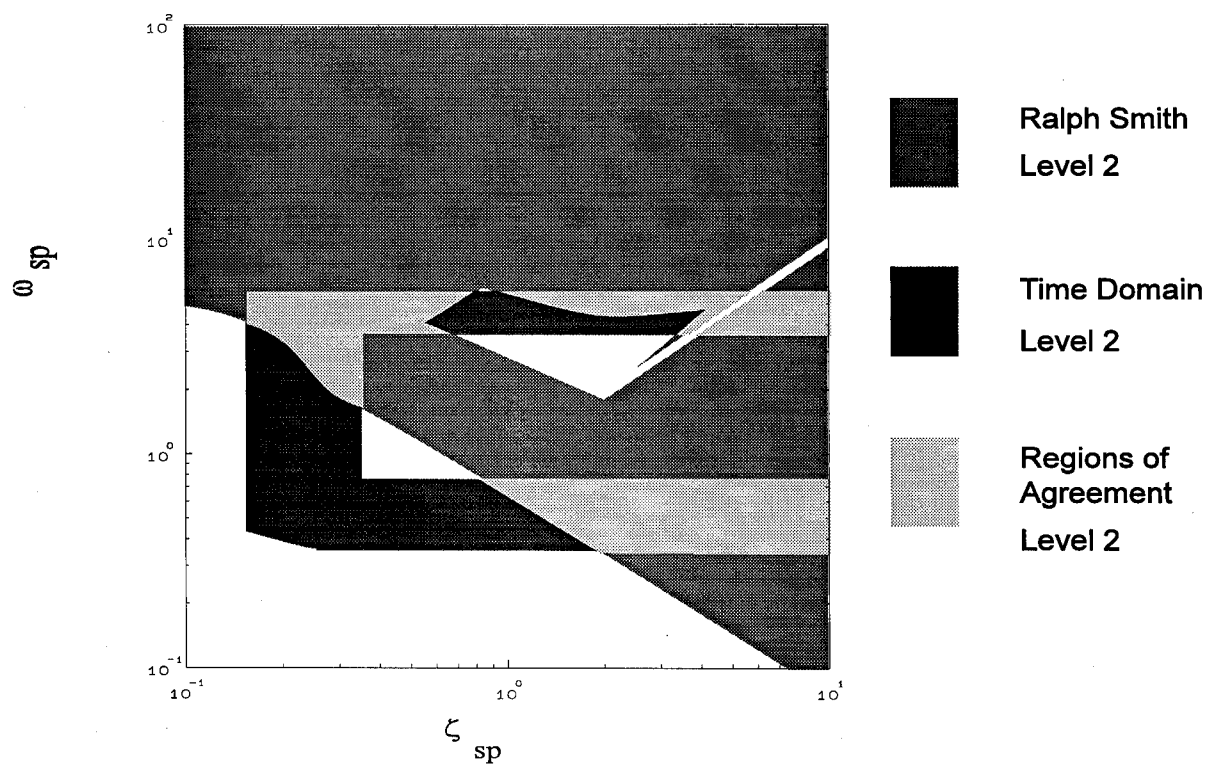


Figure C.124: Level 2 Regions (Case 21)

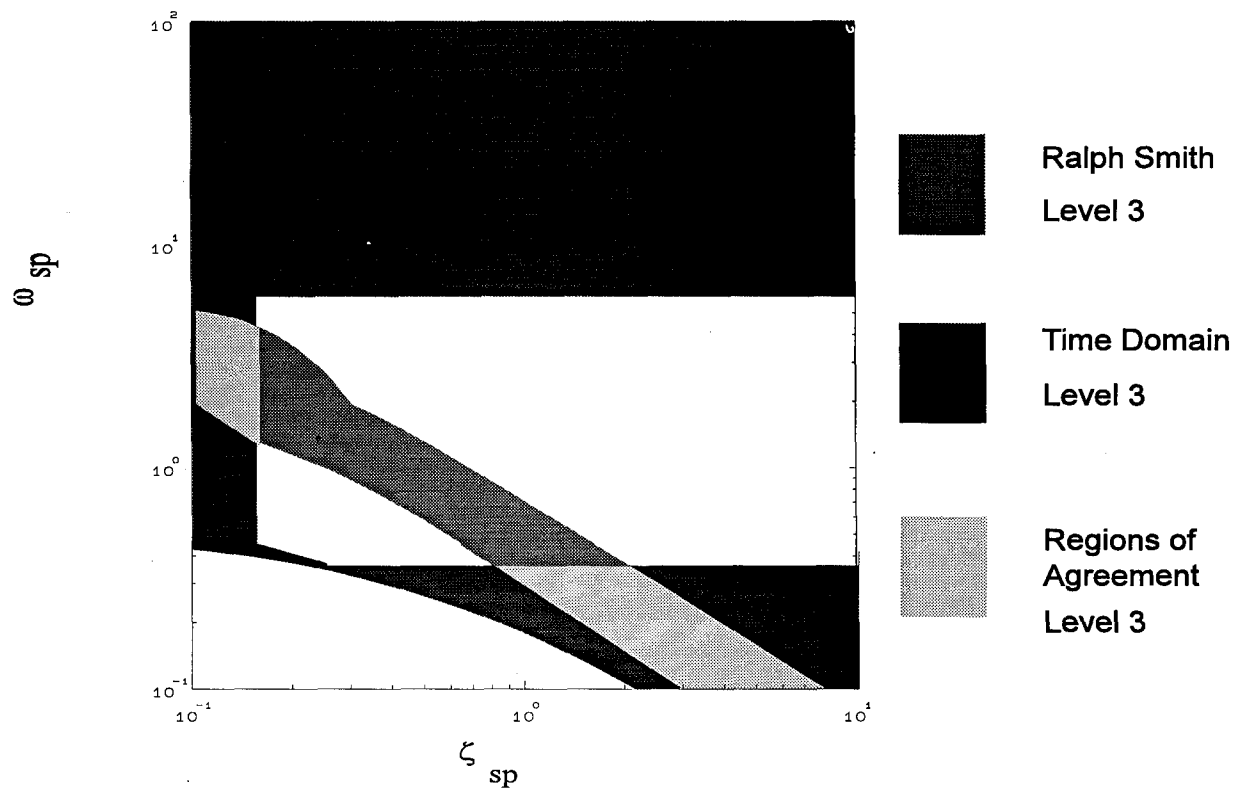


Figure C.125: Level 3 Regions (Case 21)

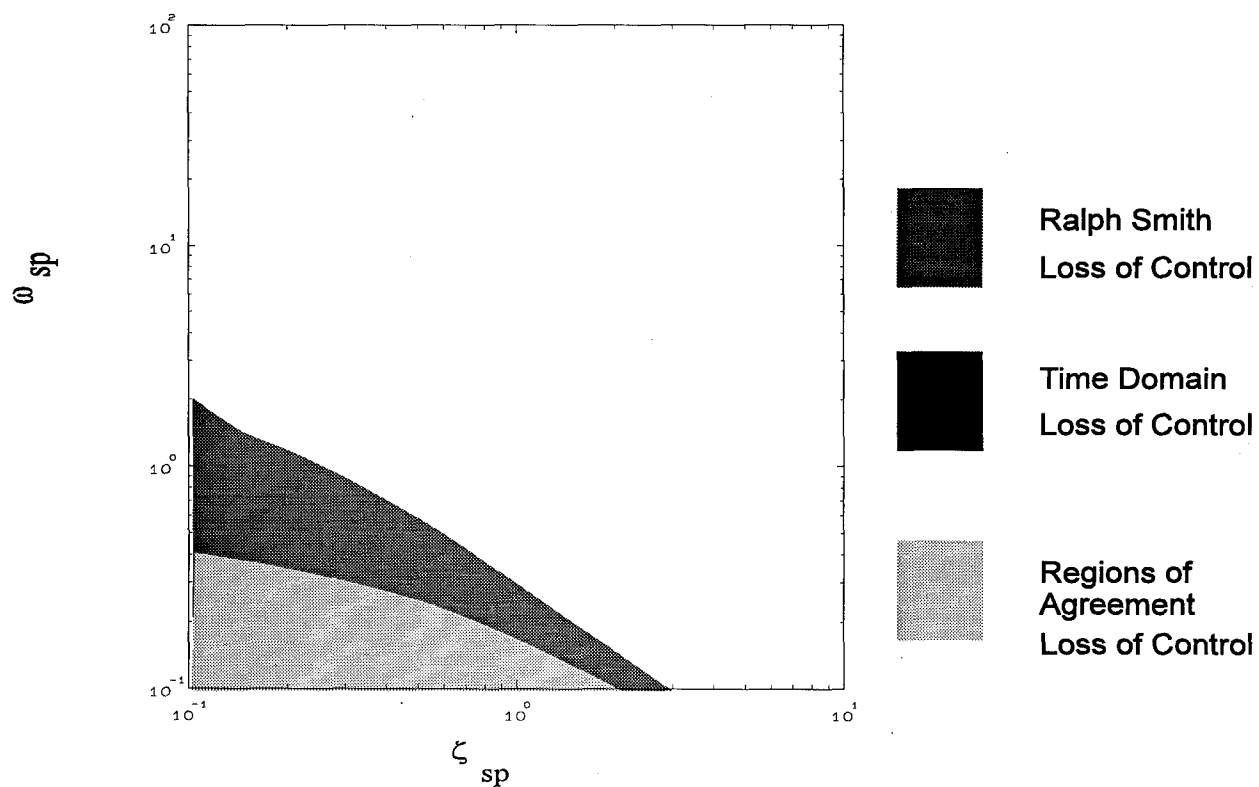


Figure C.126: Loss of Control Regions (Case 21)

C.22 Case 22

$$\frac{\theta(s)}{\delta(s)} = \frac{.1431(1.77s + 1)e^{-.1s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

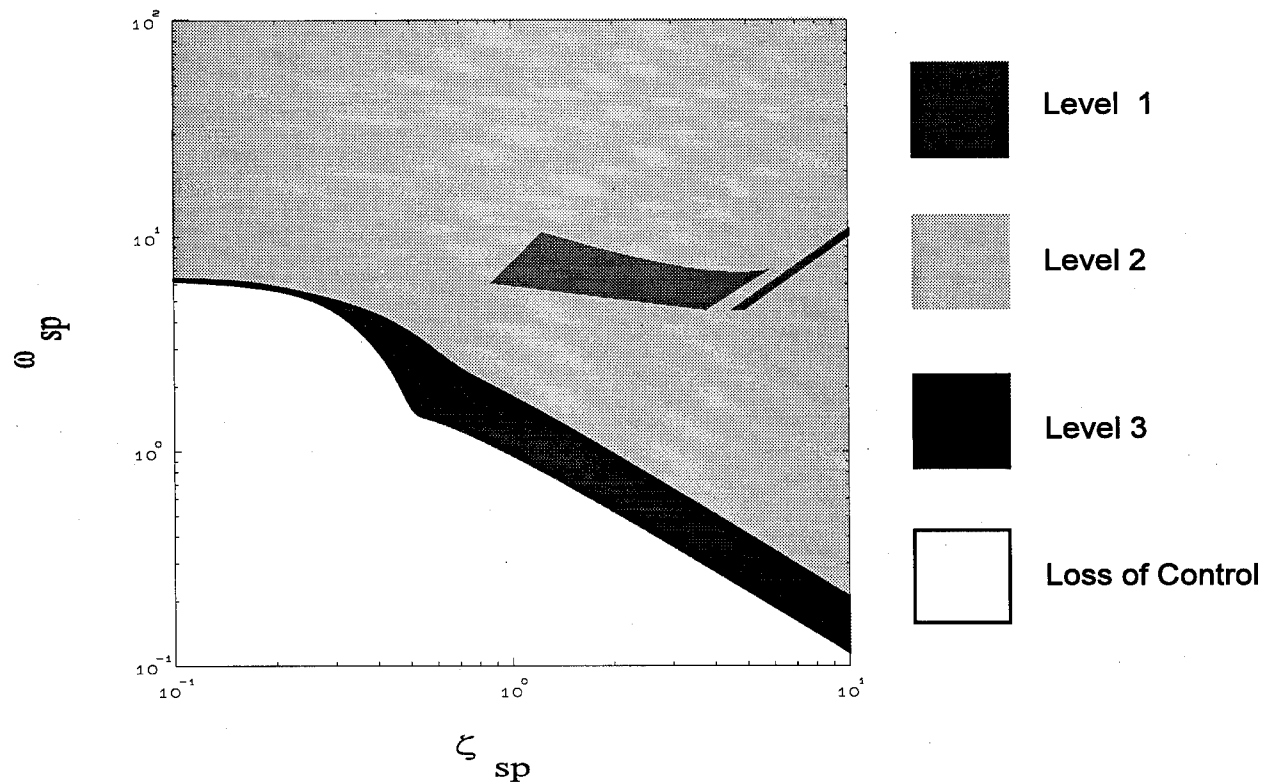


Figure C.127: Ralph Smith Criteria (Case 22)

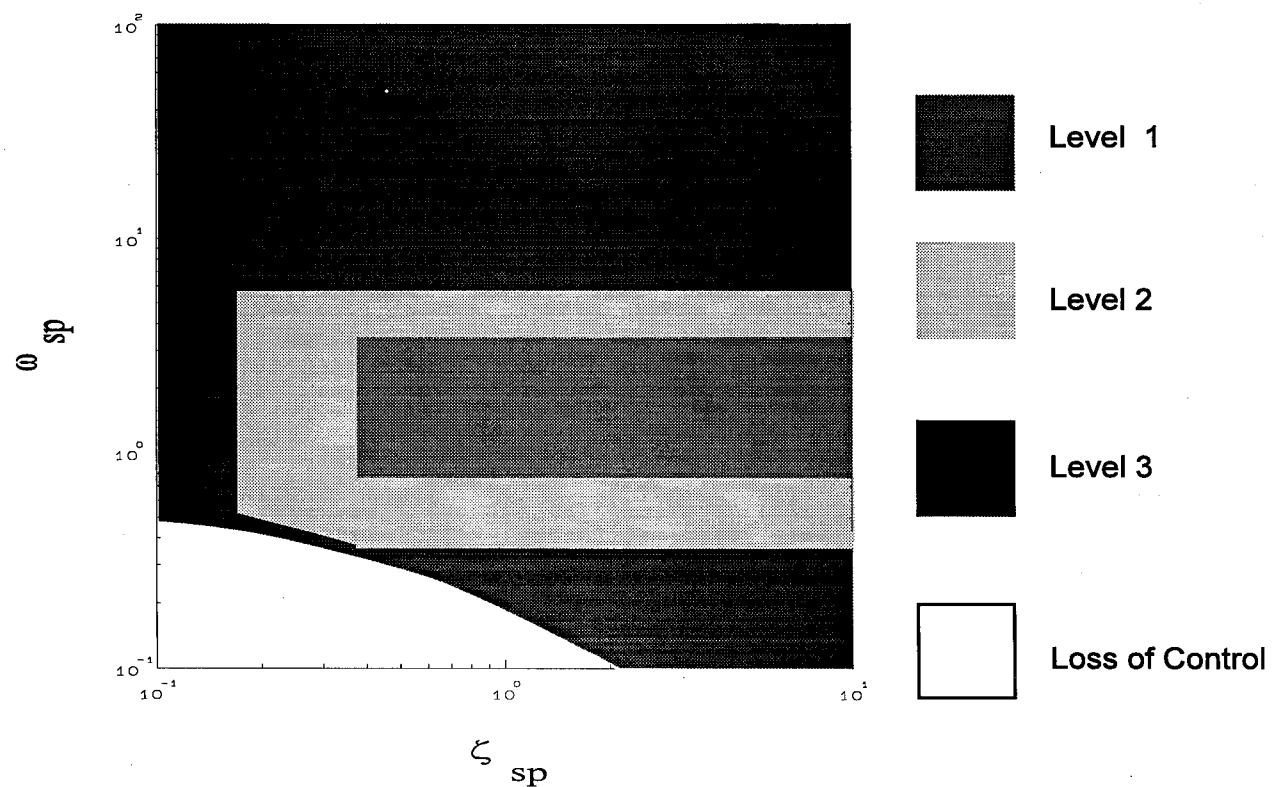


Figure C.128: Time Domain Criteria (Case 22)

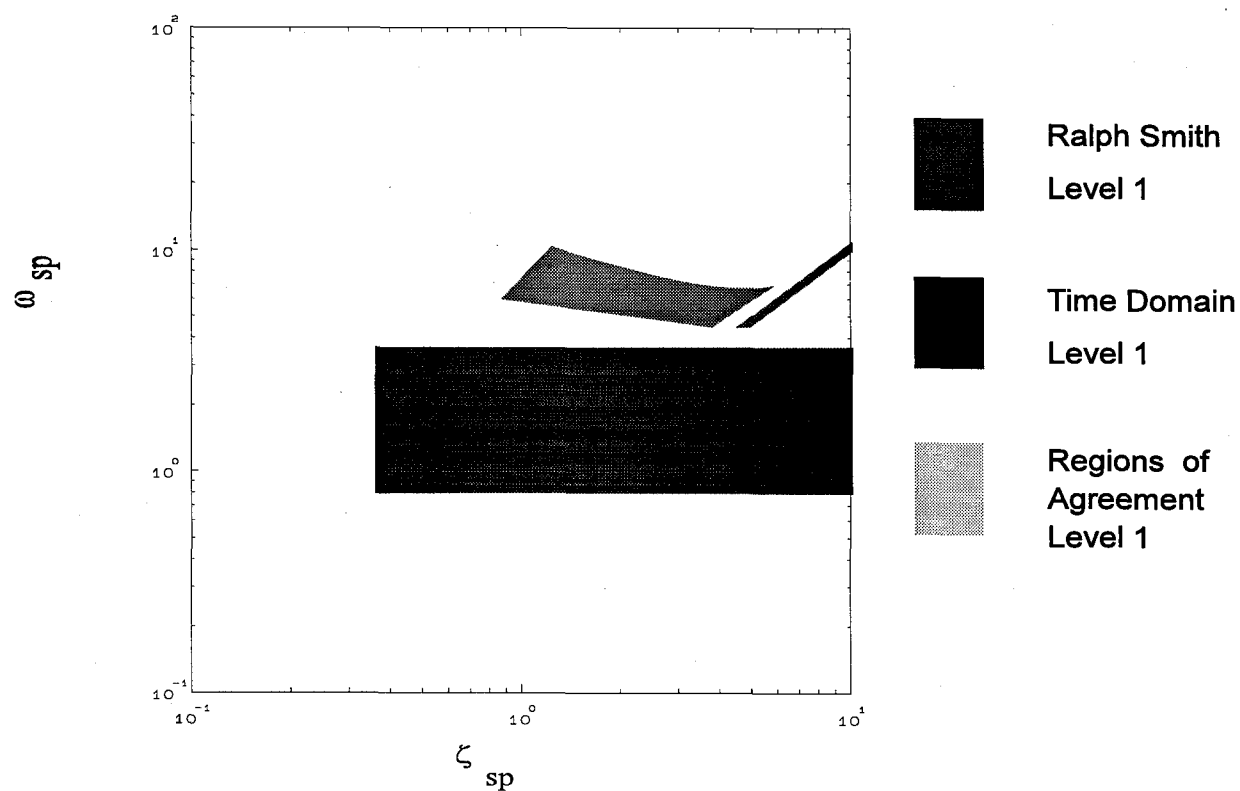


Figure C.129: Level 1 Regions (Case 22)

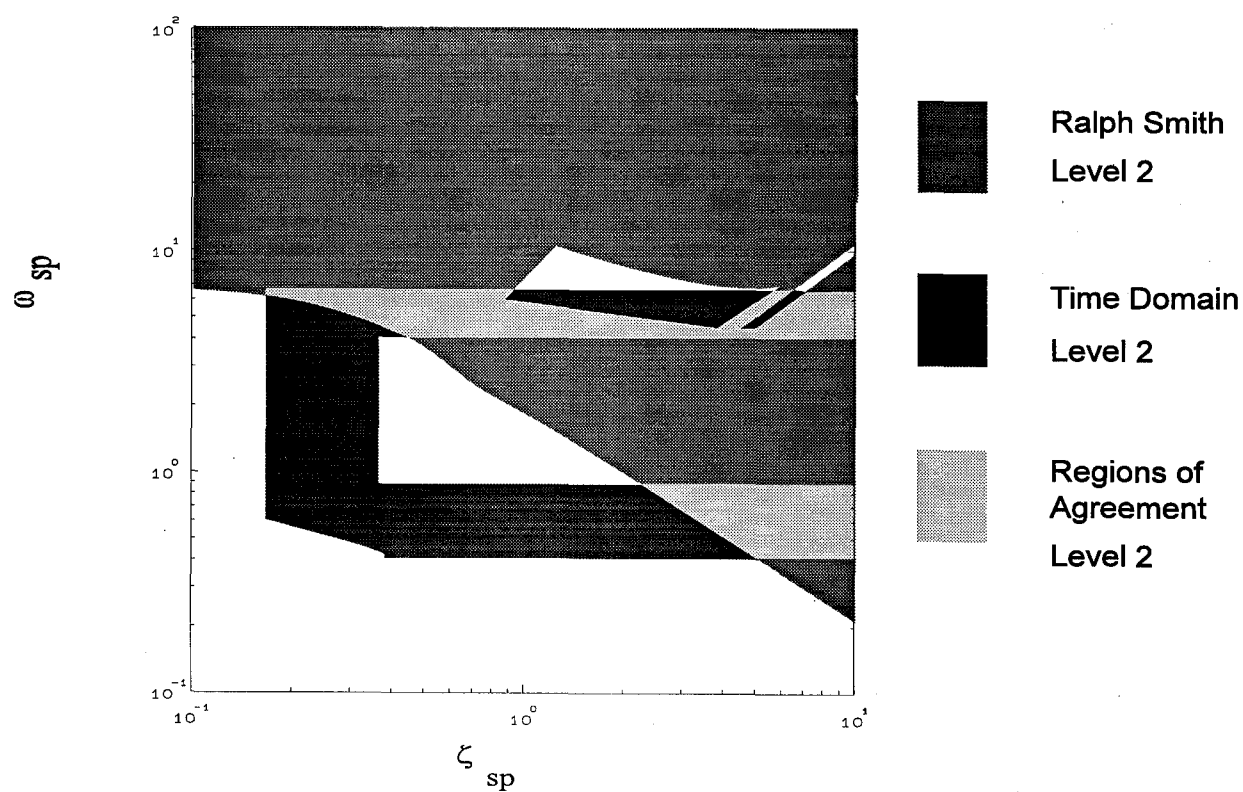


Figure C.130: Level 2 Regions (Case 22)

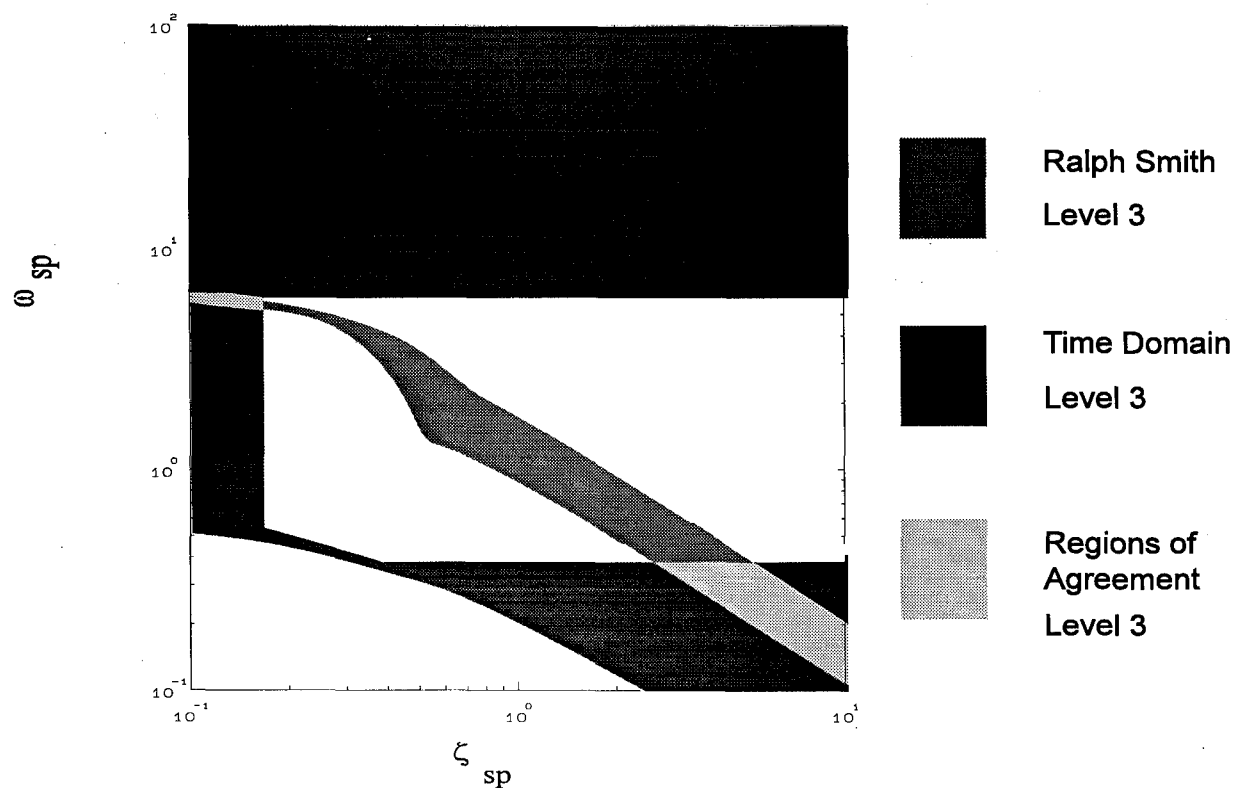


Figure C.131: Level 3 Regions (Case 22)

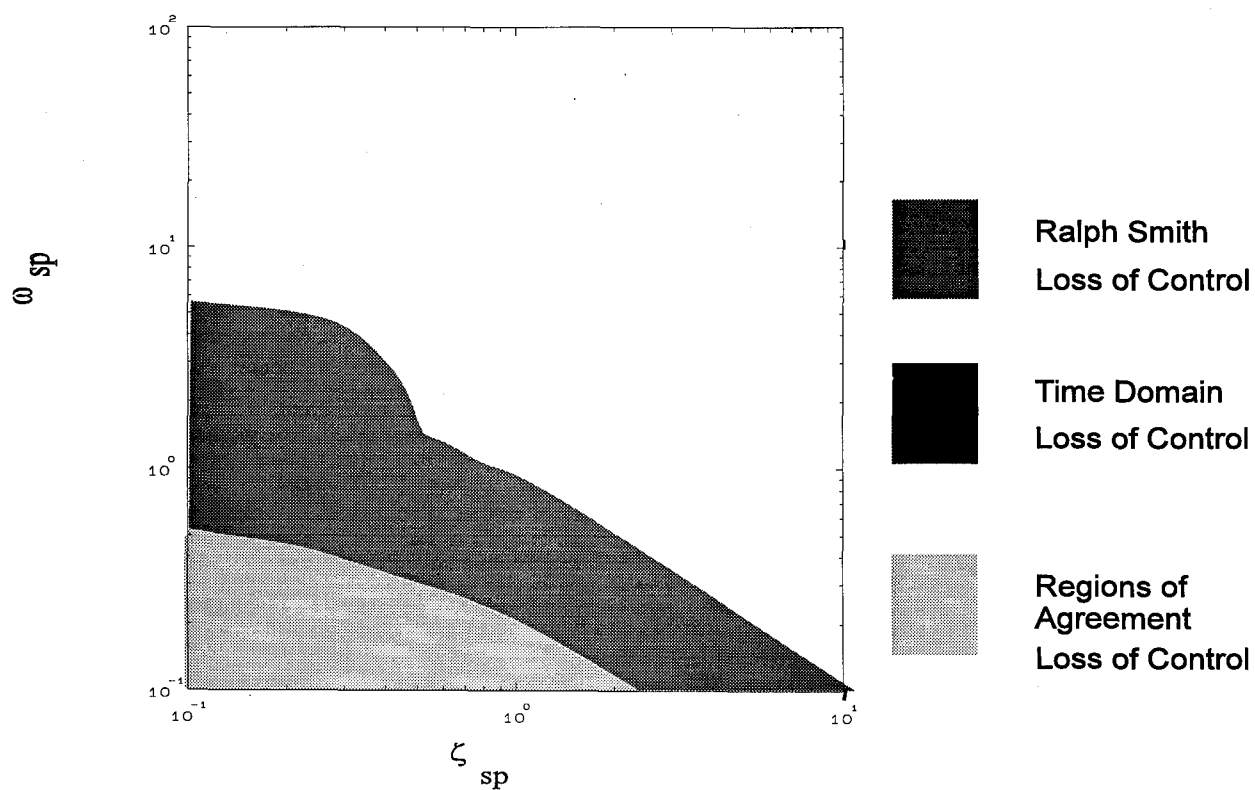


Figure C.132: Loss of Control Regions (Case 22)

C.23 Case 23

$$\frac{\theta(s)}{\delta(s)} = \frac{.1431(1.77s + 1)e^{-.15s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

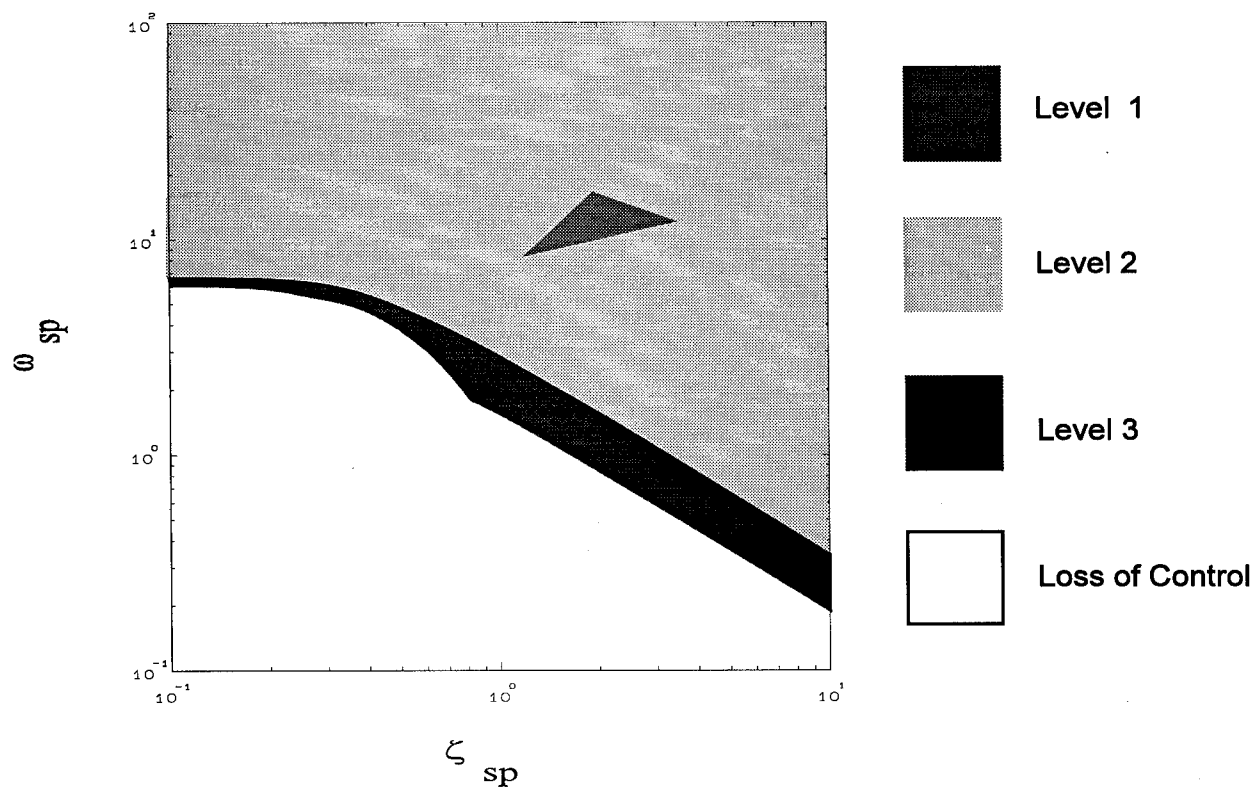


Figure C.133: Ralph Smith Criteria (Case 23)

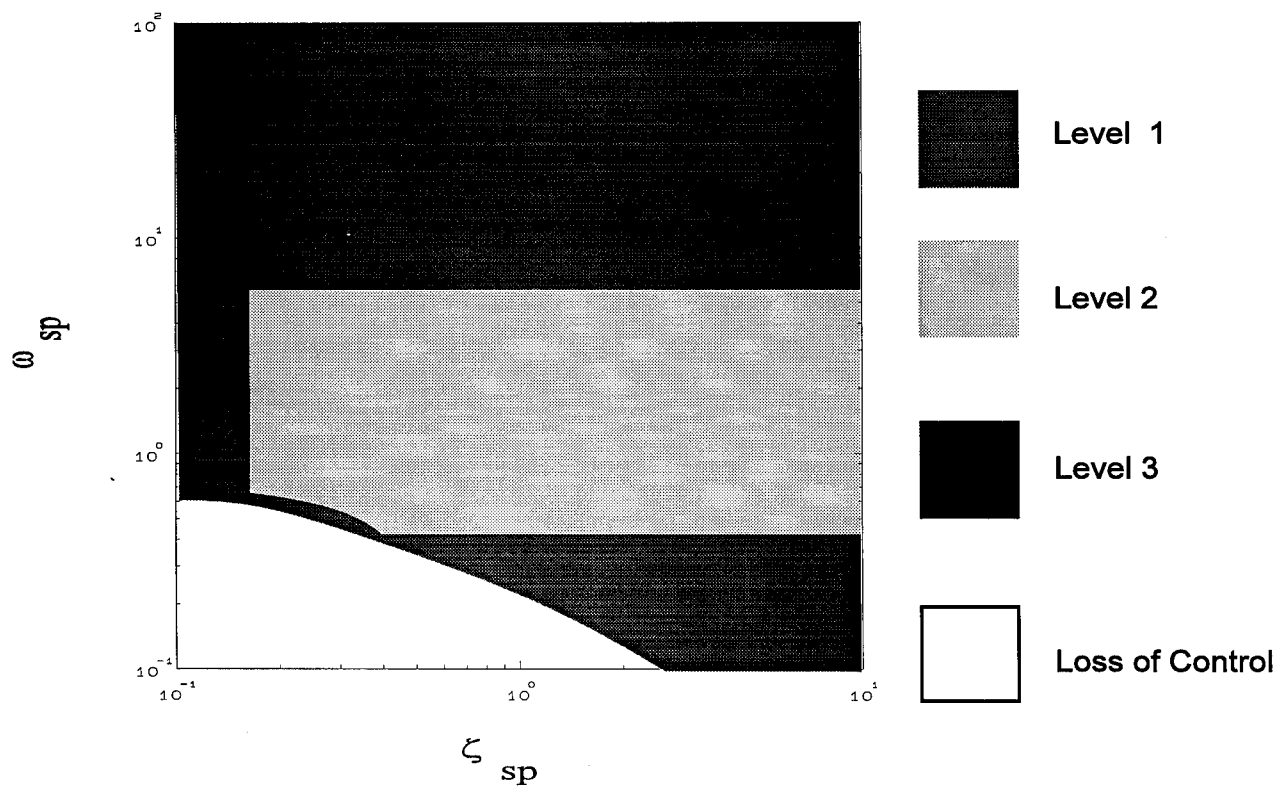
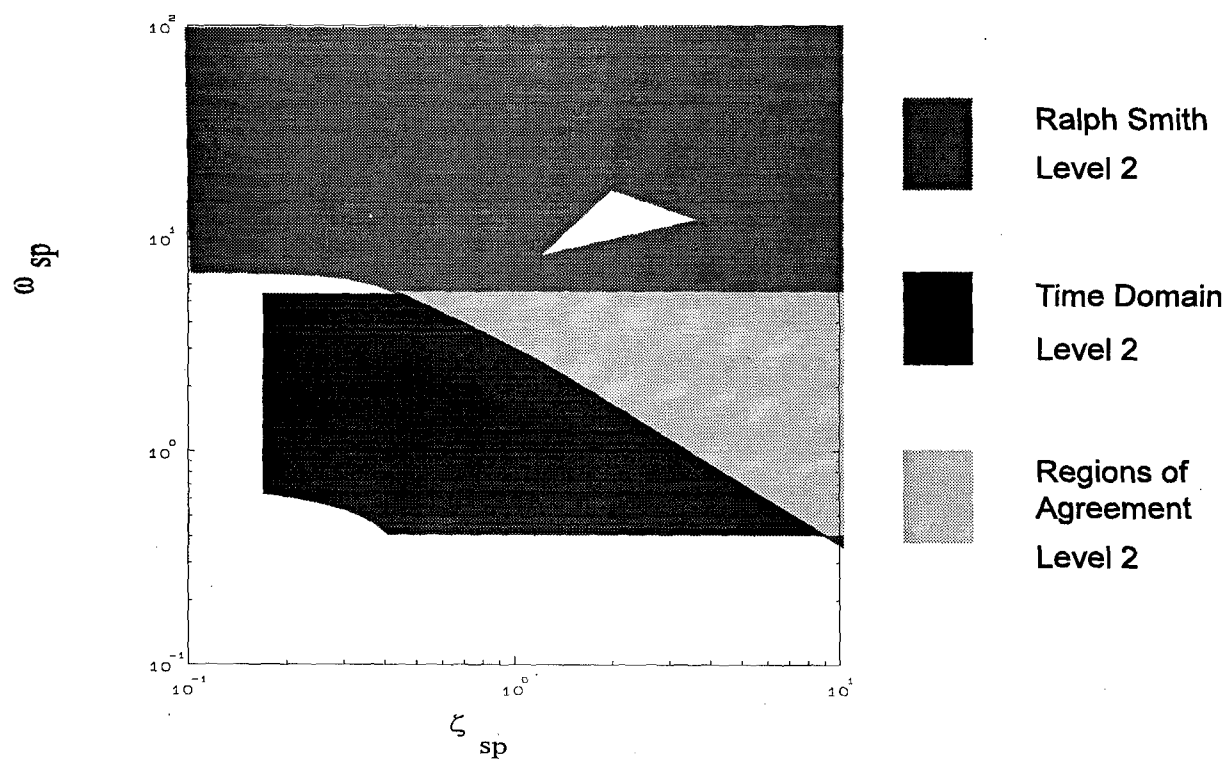
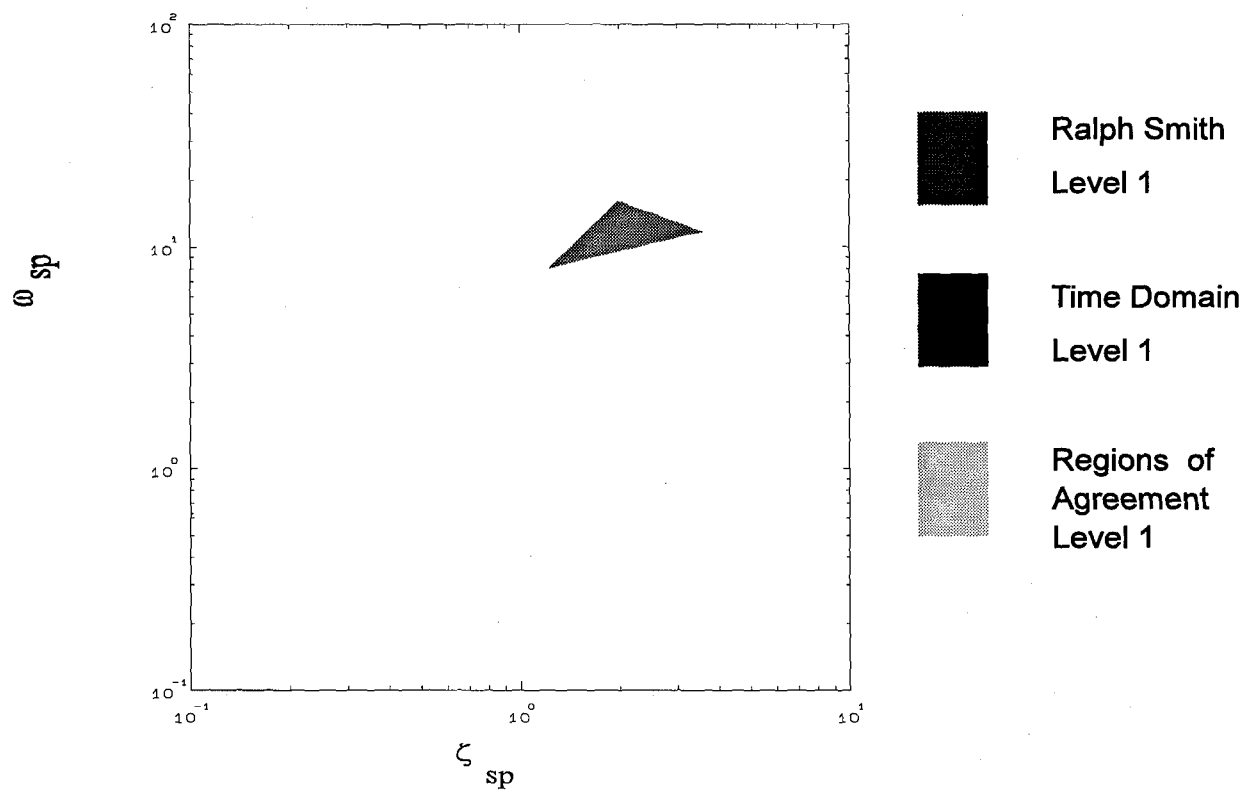


Figure C.134: Time Domain Criteria (Case 23)



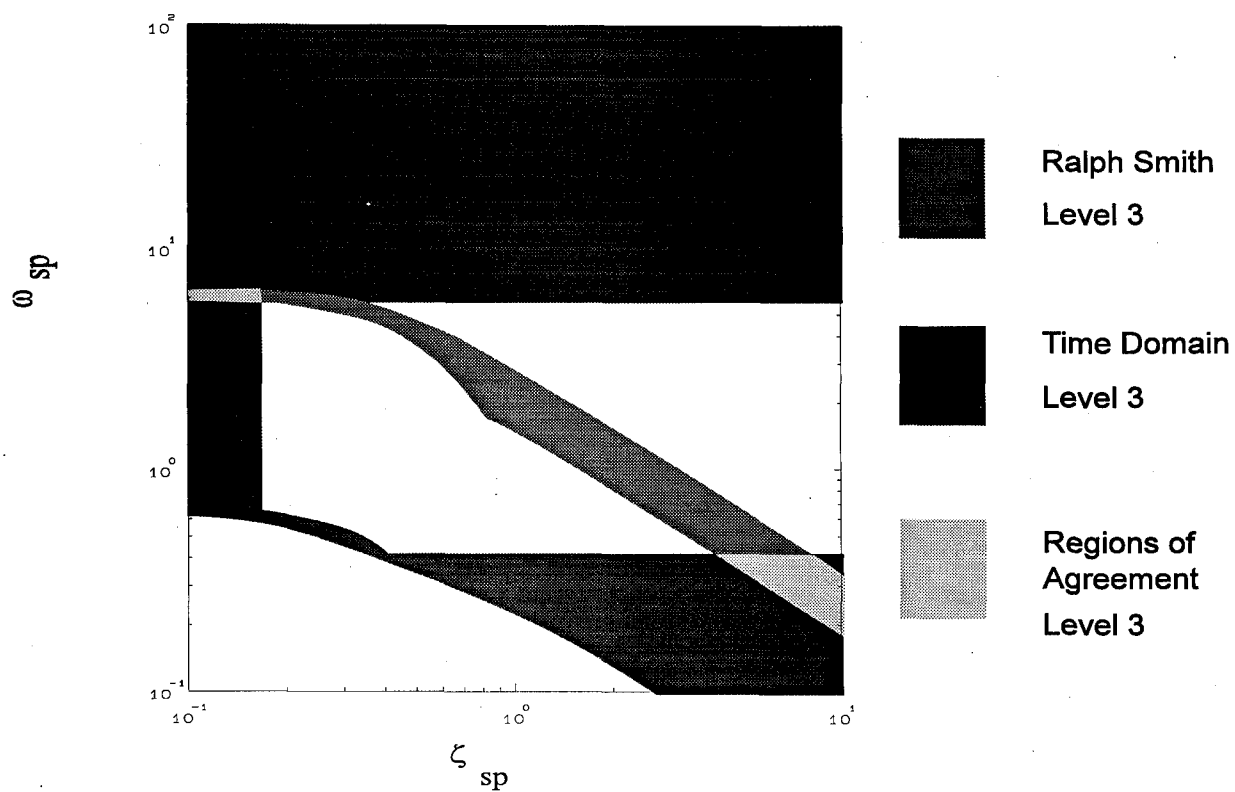


Figure C.137: Level 3 Regions (Case 23)

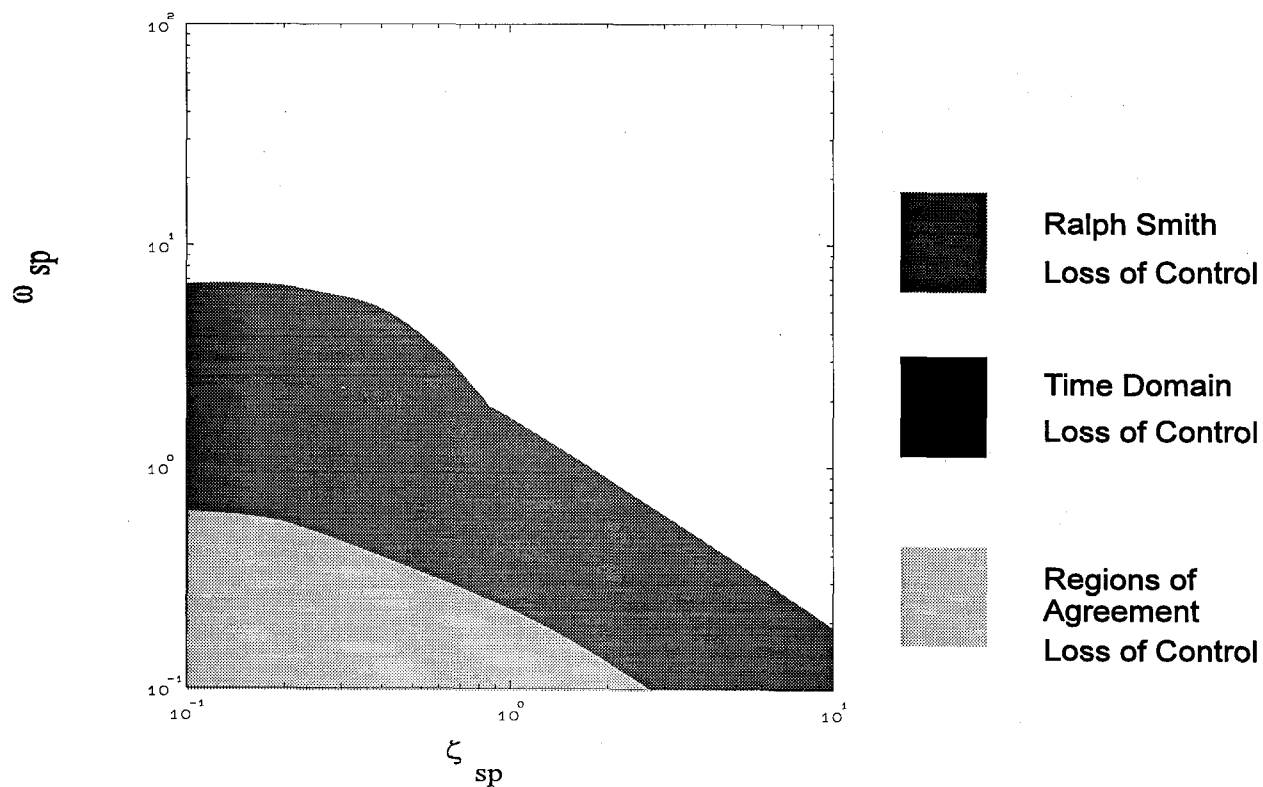


Figure C.138: Loss of Control Regions (Case 23)

C.24 Case 24

$$\frac{\theta(s)}{\delta(s)} = \frac{.1431(1.77s + 1)e^{-.2s}}{s(s^2 + 2\zeta_{sp}\omega_{sp}s + \omega_{sp}^2)}$$

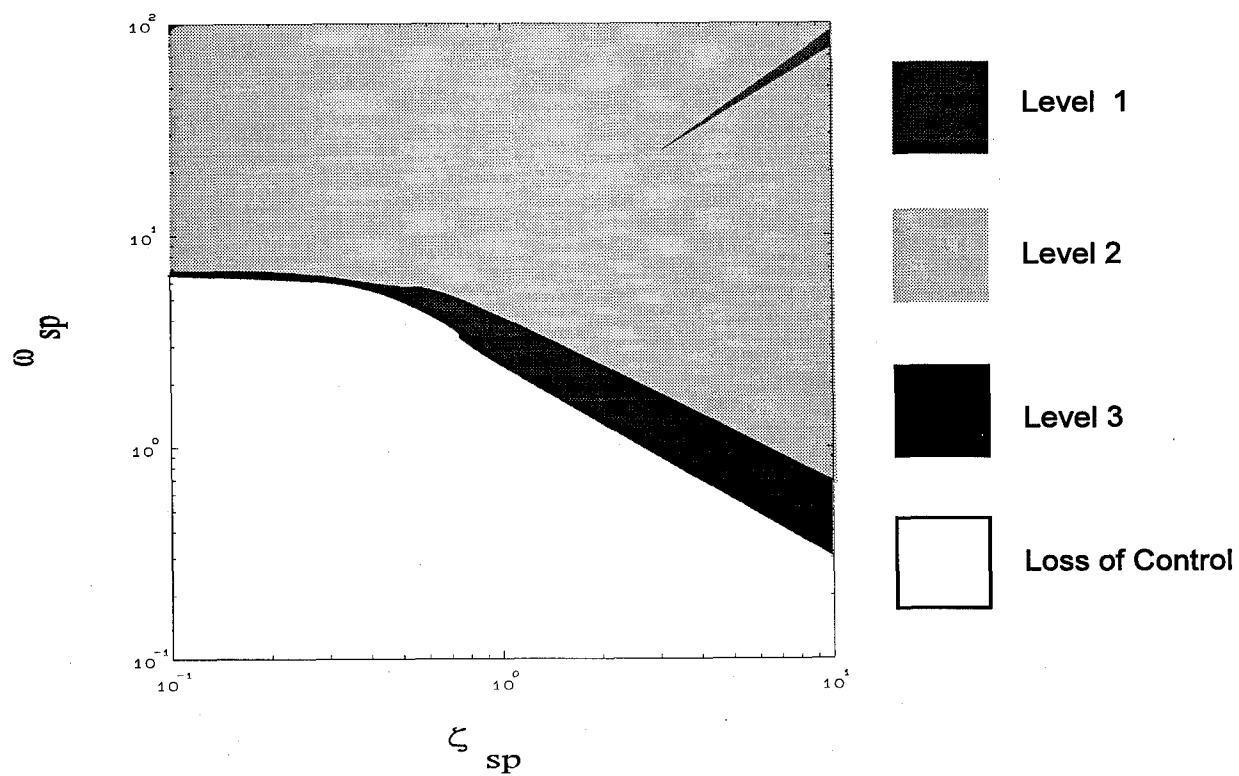


Figure C.139: Ralph Smith Criteria (Case 24)

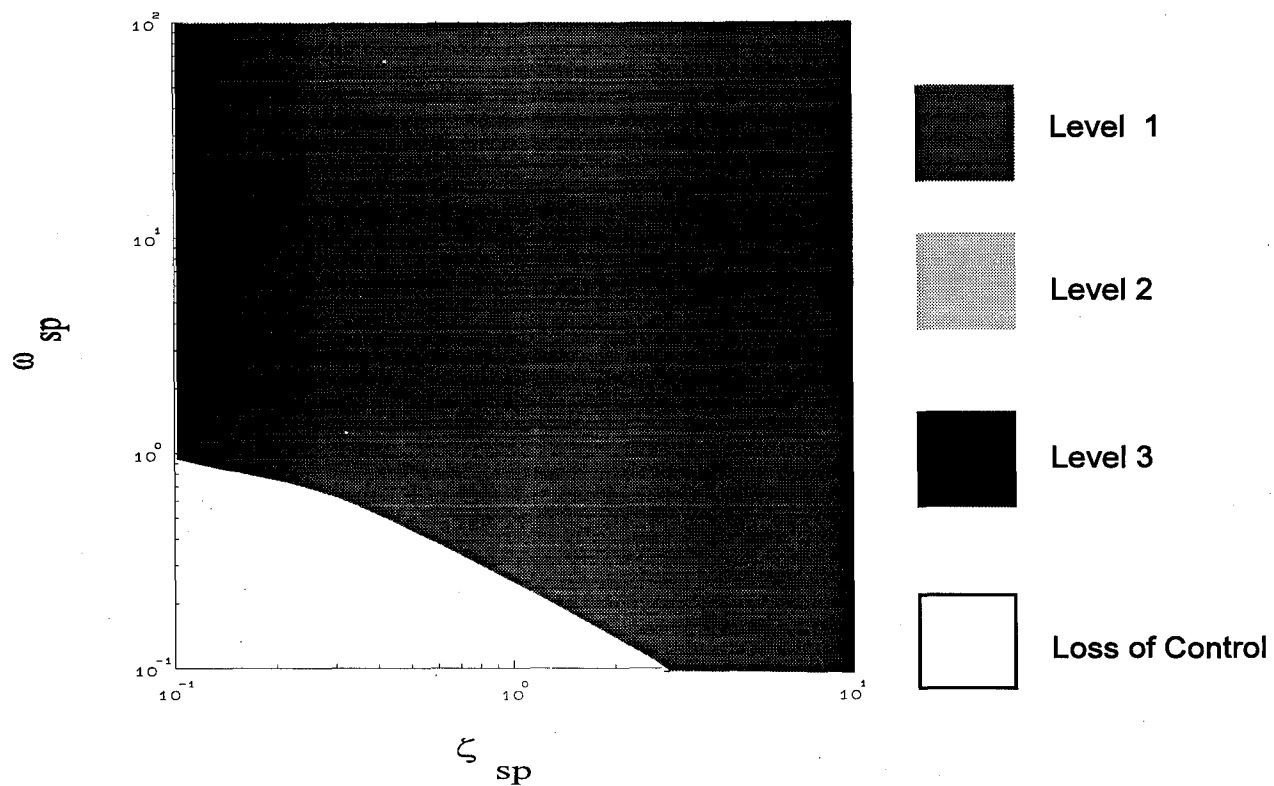


Figure C.140: Time Domain Criteria (Case 24)

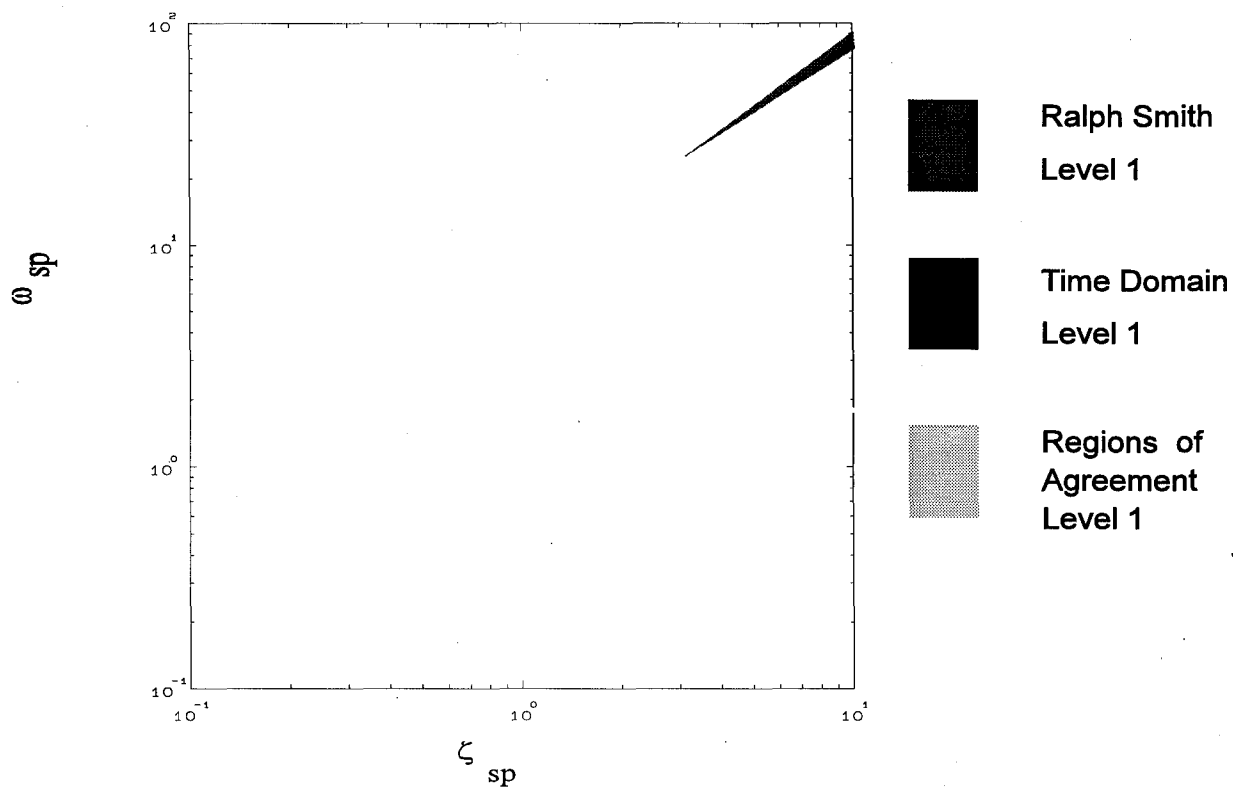


Figure C.141: Level 1 Regions (Case 24)

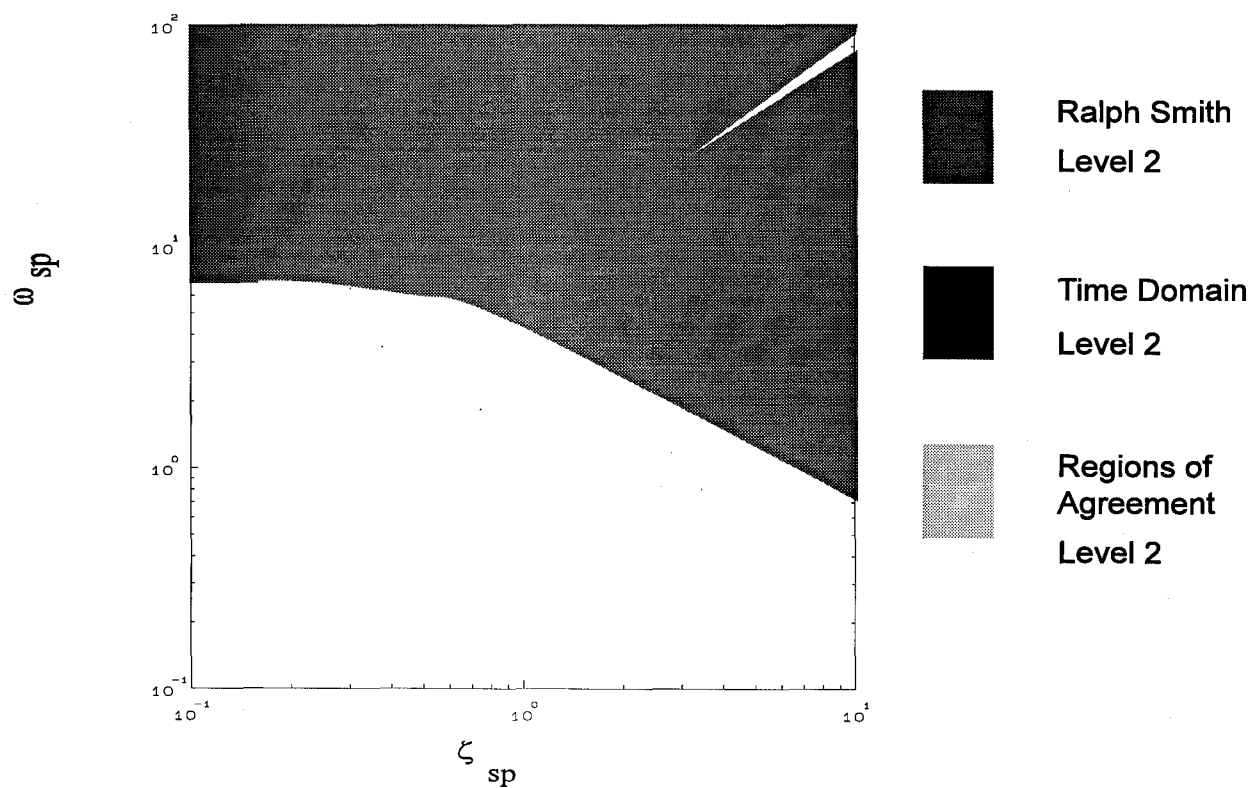


Figure C.142: Level 2 Regions (Case 24)

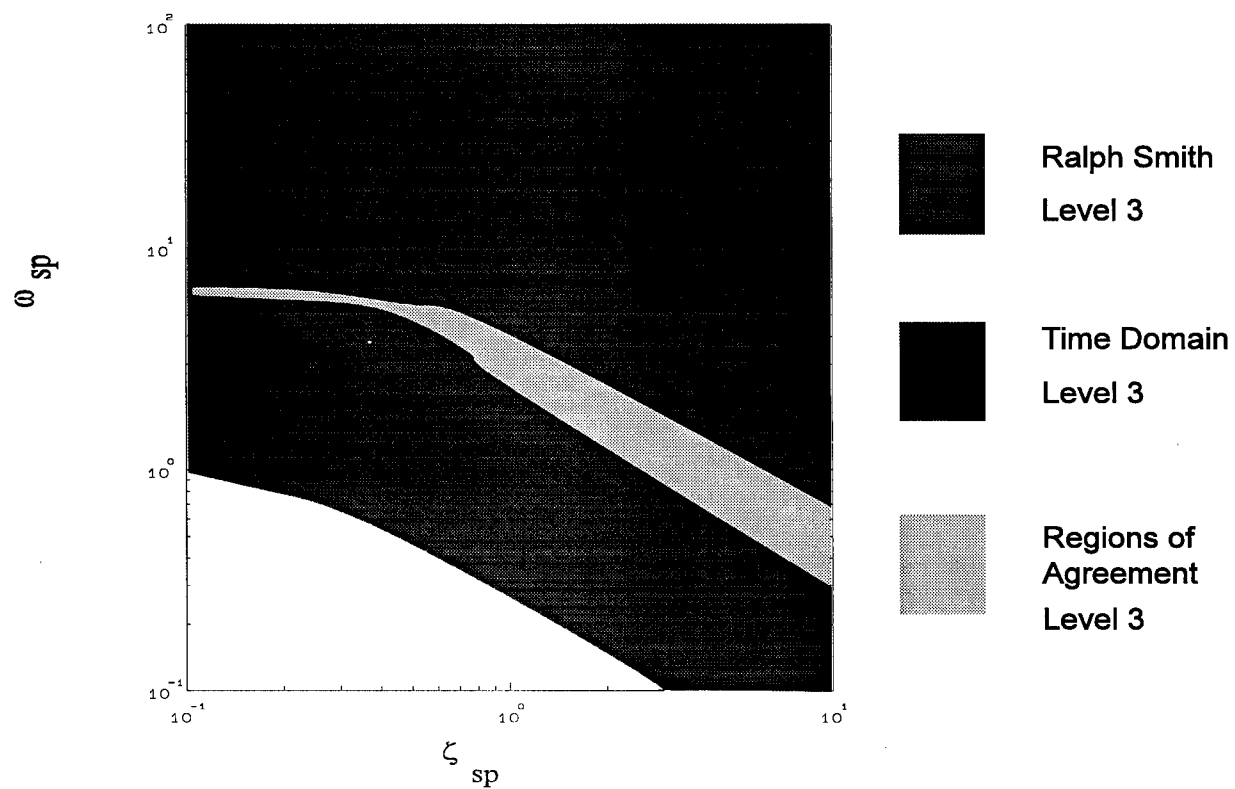


Figure C.143: Level 3 Regions (Case 24)

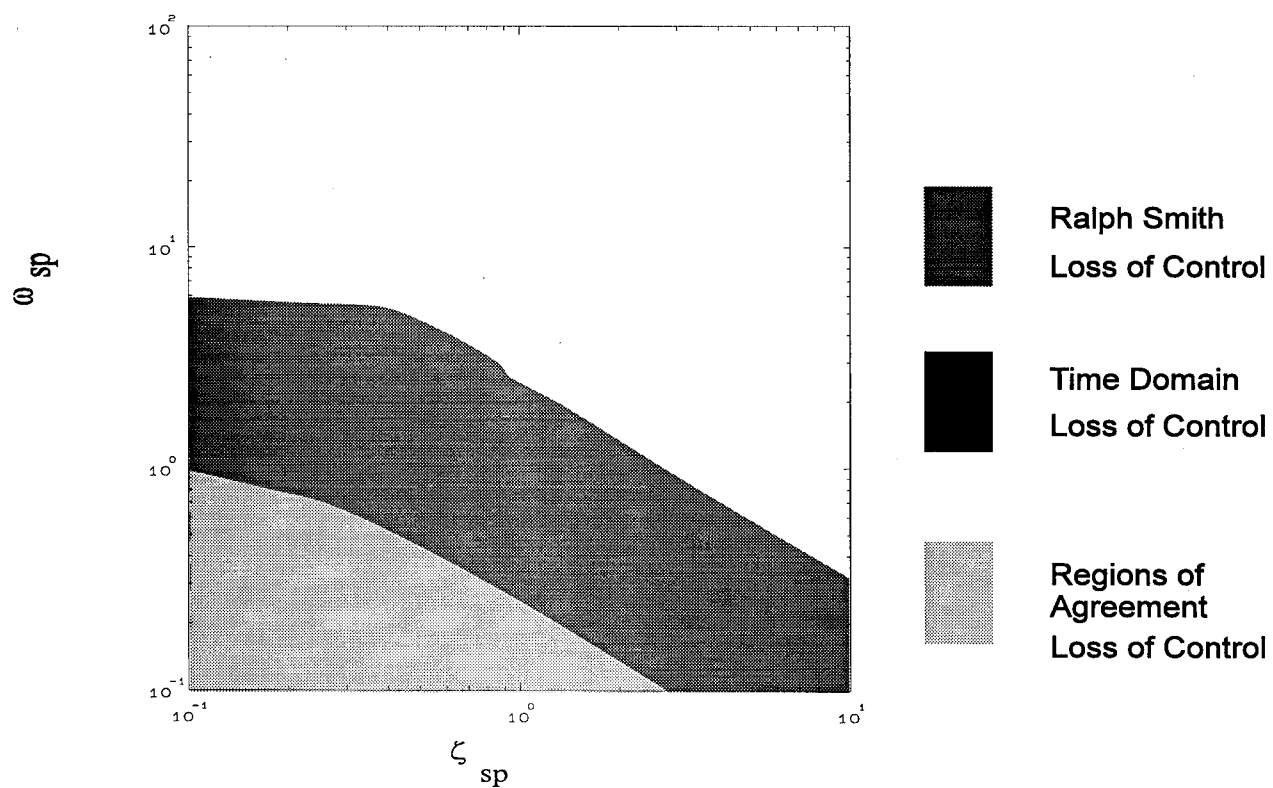


Figure C.144: Loss of Control Regions (Case 24)

Appendix D. Computer Code

The following computer code was written for MATLABTM. It consists of two script files. The first one produced the data for the mappings while the second plots the data to produce scatter plots similar to those in Appendix C.

generate.m

```
Vt=214; %velocity in ft/sec
Ttheta2=1.69;
ktheta=.1144;
tau=.15;

%Set up grid for examining criterion
zeta=logspace(-1,1,100);
wn=logspace(-1,2,100);

wnTtheta2=wn.*Ttheta2;

overall=zeros(length(wn)*length(zeta),1);

kount=1;
for i=1:length(zeta);
    for j=1:length(wn);

%create transfer function theta/deltae
num=ktheta*[Ttheta2 1];
den=[1 2*zeta(i)*wn(j) wn(j)^2 0];

%find transfer function q/deltae
[numq,denq]=minreal([num 0],den);
```

```

numq=[numq(2) numq(3)];

%create state space realization
[a,b,c,d]=tf2ss(numq,denq);

% the following lines come from step.m
% The next two constants control the precision of the plot
% and the time interval of the plot.
st=0.005; \% Set settling time bound = 0.5%
precision=30; \% Show approx 30 points for simple graph
% Step response is effectively equal to placing initial conditions
% on the plant as follows:
[n,m]=size(b);
if abs(rcond(a)) > eps
x0 = -a\b*ones(m,1);
% Cater for pure integrator case
else
x0 = ones(n,1);
end
t=timvec(a,b,c,x0,st,precision);
%
%number of points wanted for precision
pts=10000;
tconst=max(t);
tconst=tconst+tau;
%creates an ending point that is displaced by the time delay
%set up a linear time vector which starts at zero and ends at tconst with
%specified number of points
t=linspace(0,tconst,pts);

```

```

%add time delay into step input
u=stepfun(t,tau);

%simulate the response
q=lsim(numq,denq,u,t);
%plot(t,q)
%find the steady state value of the response
dcgain=-c/a*b+d;

%find qdot/deltae transfer function inorder to find slope
num1=[numq 0];
den1=[denq];

qdot=lsim(num1,den1,u,t);

%find time that max slope occurs, t(k) and point on q response
[maxslope,k]=max(qdot);
qmaxslope=table1([t' q],t(k));

m=maxslope; % slope of maxslope line

%find the time t1 where maxslope line crosses y=0
    %y=0, x=t1;
b=(qmaxslope-maxslope*t(k));
t1=-b/m;

%find level for equivalent time delay
if t1<= .12
    delaylevel(kount)=1;
elseif t1<= .17

```

```

delaylevel(kount)=2;
elseif t1<=.21
delaylevel(kount)=3;
else
delaylevel(kount)=10;
end

%find time t2, where maxslope line crosses qss
    %y=dcgain x=t2
t2=(dcgain-b)/m;

%rise time parameter, terminal flight phases
deltat=t2-t1;
if deltat>= 9/Vt & deltat<= 200/Vt
risetimelevel(kount)=1;
elseif deltat>= 3.2/Vt & deltat<= 645/Vt
risetimelevel(kount)=2;
else
risetimelevel(kount)=3;
end

%find q1, max pitch rate
[q1,k1]=max(q);

%find time to first peak
if q1 == q(length(q))                %last q (System is overdamped)
q90=.90*dcgain;                      %for overdamped system tq is defined as
Z=find(q>q90);                       % time to 90% of final value
tq=t(Z(1));
else

```



```

tq=t(k1);
end

%find time to first peak level
if tq >= .2 & tq <= .9
    tfplevel(kount)=1;
else
    tfplevel(kount)=2; %no other level are defined
end

%find deltaq1
deltaq1=q1-dcgain;

%find q2, first min
[q2,k2]=min(q(k1:pts));

%find deltaq2
deltaq2=dcgain-q2;

%allow for possibility of no min
if deltaq2<= 0
    deltaq2 = 0;
end

%allow for overdamped system
if deltaq2~=0 & deltaq1<=0
    deltaq2=0;
    deltaq1=0;
end

```

```
%Transient Peak ratio
```

```
tran=deltaq2/deltaq1;
```

```
if tran<= .3
```

```
tprlevel(kount)=1;
```

```
elseif tran<=.6
```

```
tprlevel(kount)=2;
```

```
elseif tran<=.85
```

```
tprlevel(kount)=3;
```

```
elseif tran>.85
```

```
tprlevel(kount)= 10;
```

```
else
```

```
tran=0;
```

```
tprlevel(kount)=1;
```

```
end
```

```
%produce the bode magnitude and phase plots for the transfer function
```

```
w=logspace(0,log10(6),10);
```

```
[magn,phase]=bode(num,den,w);
```

```
mag=20*log10(magn); %put mag in dB
```

```
%find slope on interval of 1<w<6
```

```
A=[log10(w)' ones(10,1)];
```

```
slope=inv(A'*A)*(A'*mag);
```

```
S=.3*slope(1); %-20db/dec=-6db/oct
```

```
%Determine the Level based on slope
```

```
if S < -2
```

```
slopelevel(kount)=1;
```

```
else
```

```
slopelevel(kount)=2;
```

```
end
```

```
%Find criterion Frequency
```

```
wc=.24*S+6;
```

```
%Create larger interval for bode plot
```

```
w1=logspace(-2,2,300);
```

```
[mag1,phase1]=bode(num,den,w1);
```

```
mag2=20*log10(mag1);
```

```
Phase=phase1-tau*w1'*180/pi;      %Adds in Time delay
```

```
%Determine the phase angle at the criterion frequency
```

```
lag=table1([w1' Phase],wc);
```

```
%Find Phase Lag level
```

```
if lag > -123
```

```
laglevel(kount)=1;
```

```
elseif lag <= -123 & lag > -165
```

```
laglevel(kount)=2;
```

```
elseif lag <= -165 & lag > -180
```

```
laglevel(kount)=3;
```

```
else
```

```
laglevel(kount)=10;
```

```
end
```

```
% overall flying qualities level
```

```

timedomain(kount)=max([delaylevel(kount) risetimelevel(kount) tprlevel(kount)]);
RS(kount)=max([tfplevel(kount) slopelevel(kount) laglevel(kount)]);

%create data matrices
%Ralph Smith Data
RSdata(kount,:)= [zeta(i) wnTtheta2(j) RS(kount) tfplevel(kount) ...
slopelevel(kount) laglevel(kount)];

%Time Domain Data
TDdata(kount,:)= [zeta(i) wnTtheta2(j) timedomain(kount) delaylevel(kount) ...
risetimelevel(kount) tprlevel(kount)];

%Data for both criteria
rawdata(kount,:)= [zeta(i) wnTtheta2(j) t1 Vt*deltat tran timedomain(kount) ...
tq S lag RS(kount) wn(j)];

kount=kount+1;

end

end

save /tmp_mnt/home/dynamics/lcarlucc/thesis/cases/f16_2.mat

exit

```

dataplot.m

%%%%%%%%%

%Maps Time Domain

%%%%%%%%%

count=1;

figure

loglog(0,0,'k.')

xlabtex([gtex('z'),stex('sp')]);

ylabtex([gtex('w'),stex('sp')])

hold

for i=1:length(zeta);

 for j=1:length(wn);

 if timedomain(count) ==1

 loglog(zeta(i),wn(j),'rx')

 elseif timedomain(count) == 2

 loglog(zeta(i),wn(j),'yx')

 elseif timedomain(count) == 3

 loglog(zeta(i),wn(j),'bx')

 end

 count=count+1;

end

end

%%%%%%%%%

%maps Ralph Smith

%%%%%%%%%

count=1;

figure

loglog(0,0,'k.')

```

xlabtex([gtex('z'),stex('sp')]);
ylabtex([gtex('w'),stex('sp')])
hold
for i=1:length(zeta);
    for j=1:length(wn);
        if RS(count) ==1
            loglog(zeta(i),wn(j),'rx')
        elseif RS(count) == 2
            loglog(zeta(i),wn(j),'yx')
        elseif RS(count) == 3
            loglog(zeta(i),wn(j),'bx')
        end
        count=count+1;
    end
end
end

```

```

%%%%%%
%Maps level 1 of TD, RS
%%%%%%
count=1;
figure
loglog(0,0,'k.')
xlabtex([gtex('z'),stex('sp')]);
ylabtex([gtex('w'),stex('sp')])
hold
for i=1:length(zeta)
for j=1:length(wn);

if timedomain(count) ==1
loglog(zeta(i),wn(j),'bo')

```

```

end
if RS(count)==1
loglog(zeta(i),wn(j),'yx')
end

count=count+1;
end
end

%%%%%%
%Maps level 2 of RS,TD
%%%%%%
count=1;
figure
loglog(0,0,'k.')
xlabel([gtex('z'),stex('sp')]);
ylabel([gtex('w'),stex('sp')])
hold
for i=1:length(zeta)
for j=1:length(wn);

if timedomain(count) ==2
loglog(zeta(i),wn(j),'bo')
end
if RS(count)==2
loglog(zeta(i),wn(j),'yx')
end

count=count+1;
end

```

```

end

%%%%%%%%
%Maps level 3 of TD, RS
%%%%%%%%
count=1;
figure
loglog(0,0,'k.')
xlabel([gtex('z'),stex('sp')]);
ylabel([gtex('w'),stex('sp')])
hold
for i=1:length(zeta)
for j=1:length(wn);
if timedomain(count) ==3
loglog(zeta(i),wn(j),'bo')
end
if RS(count)==3
loglog(zeta(i),wn(j),'yx')
end

count=count+1;
end
end

%%%%%%%%
%Maps level 10 of TD, RS
%%%%%%%%
count=1;
figure
loglog(0,0,'k.')

```



```

xlabtex([gtex('z'),stex('sp')]);
ylabtex([gtex('w'),stex('sp')])
hold
for i=1:length(zeta)
for j=1:length(wn);
if timedomain(count) ==10
loglog(zeta(i),wn(j),'bo')
end
if RS(count)==10
loglog(zeta(i),wn(j),'yx')
end

count=count+1;
end
end

```

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